

NonRelativistic Rotating Bosons via Complex Langevin

Casey E. Berger

February 19, 2021

Contents

1	Notes To Self and To-Do List	2
1.1	Updates to make in the notes	2
1.1.1	TO DO	2
1.1.2	DONE	2
1.2	General Notes and Reminders	3
1.2.1	Stuff to look into	3
1.2.2	Ideas	3
1.2.3	Goals:	3
2	The Method: Complex Langevin	5
2.1	The rotating bosonic gas	5
2.1.1	The Action	5
2.2	The Langevin Equations	6
2.3	Observables	8
2.3.1	Observables averaged over the volume	8
2.3.2	Observables per site	9
	Appendices	10
A	NRRB Derivations	11
A.1	Justification for the Form of the Non-Relativistic Lattice Action	11
A.2	Writing the Complex Action in Terms of Real Fields	13
A.3	Generating the NRRB CL Equations	14
A.3.1	Derivatives on the Lattice	14
A.3.2	Computing the derivative of the action with respect to the real fields	15
A.3.3	NOT UPDATED YET:Second Complexification of Drift Function	17
A.4	Lattice Observables	19
A.4.1	Density	20
A.4.2	Local Density	21
A.4.3	Field Modulus Squared	21
A.4.4	Angular Momentum	22
A.4.5	Harmonic Trapping Potential Energy	23
A.4.6	Interaction Potential Energy	24
A.4.7	Kinetic Energy	26
A.4.8	Action	26
A.4.9	Total Energy	26
A.4.10	Circulation	27

Chapter 1

Notes To Self and To-Do List

1.1 Updates to make in the notes

1.1.1 TO DO

- CHECK: in the part of the action that is multiplied by $e^{\bar{\mu}}$, you have a δ_{ab} and then both fields are labeled a – is one of those supposed to be labeled b ? (i.e. did you already take the kronecker delta in your head?) **[NOTE: It doesn't matter – they actually end up the same, but maybe change the second a to b for consistency]**
- Second complexify the drift function
- Add detailed notes on scaling – looks like the equation from your talk with Joaquin in your notes is incorrect – $\beta = N_\tau * d\tau$, not the inverse.
- Add a section on running the code?

1.1.2 DONE

- Double check the discretization of $S_{\tau,r} = \phi_r^* \phi_r - \phi_r^* e^{d\tau\mu} \phi_{r-\hat{\tau}}$
- Double check the discretization of $S_{\nabla,r} = \frac{d}{m} \phi_r^* \phi_r - \frac{1}{2m} \sum_{i=\pm x,y} \phi_r^* \phi_{r+\hat{i}}$
- Double check the discretization of $S_{\text{tr},r} = \frac{m}{2} \omega_{\text{trap}}^2 (x^2 + y^2) \phi_r^* \phi_{r-\hat{\tau}}$
- Double check the discretization of $S_{\omega,r} = i\omega_z [(x - y) \phi_r^* \phi_{r-\hat{\tau}} - \tilde{x} \phi_r^* \phi_{r-\hat{y}-\hat{\tau}} + \tilde{y} \phi_r^* \phi_{r-\hat{x}-\hat{\tau}}]$
- Double check the discretization of $S_{\text{int},r} = \lambda (\phi_r^* \phi_{r-\hat{\tau}})^2$
- Copy derivation from GoodNotes – discretization updated (the version in this doc is correct, the new one is just more clear where the factors of a go, which don't matter for now because we've set $a = 1$)
- check signs in Appendix A.1
- Double check the math when you write $\phi = \phi_1 + i\phi_2$ (in Appendix A.2)
- Determine a more natural way to write the interaction term in Appendix A.2

- Update notes to be more explicit about multidimensional cases... We're using $d = 2$, but we want to generalize this. Is the best way to write it generally? Or to derive it in all three dimensions separately?
- Double check the derivation of the drift functions (in Appendix A.3)
- Double check the derivation of the observables (in Appendix A.4).
- Complexify the observables.

1.2 General Notes and Reminders

*note that all interaction in this system is entirely governed by λ

1.2.1 Stuff to look into

- From Ref. [?] (see master lit review for citation):
 “A balance between the kinetic energy [see ref in lit review] and the interaction energy [see ref in lit review], viz. Eq. (10), of a BEC leads to a typical length scale called coherence length [see ref in lit review] for a weakly interacting BEC [11]. This quantity is relevant for super-fluid effects. For instance, it provides the typical size of the core of quantized vortices [7, 11, 13]. ”
- From ref. [?] (see master lit review for citation):
 “The vortex nucleation process in a rotating scalar Bose- Einstein condensate provides a unique model system to study the emergence of a quantum phase transition from the microscopic few-body regime to the thermodynamic limit. Even in the presence of interactions, the nucleation process of the first vortex is associated with exact linearity of the ground state energy as a function of angular momentum which leads to a discontinuous transition between the non-rotating ground state and the unit vortex.”

1.2.2 Ideas

Might it be feasible to program a GPU for the CL evolution? It could then simultaneously update the lattice very quickly.

Other methods:

- Path Optimization Method (Ohnishi et al)
- Tensor Network Systems (Banuls et al)
- World Line Methods??

1.2.3 Goals:

1. Reproduce results of Gert Aarts paper - COMPLETED
2. Reproduce the free gas - COMPLETED (Not for AMReX yet)

3. Check against virial theorems for trapped bosons - IN PROGRESS

I'm not sure that I can check the virial theorem here... how would I calculate kinetic energy only? Also we have rotation, interaction, and trap, not just trap.

4. Compare with Hayata/Yamamoto paper - IN PROGRESS

5. Some new directions to take it:

- Fixed values of angular momentum
- Polarized bosons
- Mass-imbalanced bosons
- Efimov effect and 3-body forces
- Some interesting problems in $2 + 1$ dimensions
- Virial coefficients for bosons at unitarity (maybe talk to Chris)
- Auxiliary field to represent interaction - will allow us to study phase transitions as a function of N_f ***
- Can we ever find a way to vary the dimensionality continuously?

Chapter 2

The Method: Complex Langevin

2.1 The rotating bosonic gas

Hard wall boundary conditions in space and periodic (bosonic) in time. Nonrelativistic dispersion, harmonic trapping potential centered at the midpoint of the lattice, rotation about the midpoint of the lattice in 2 dimensions, and contact interaction (delta function).

For rotation, we need at least $2 + 1$ dimensions. I will derive all equations for the general $d + 1$ dimensional case, but initial computational tests will all be in $2 + 1$ dimensions.

Our path integral for the system is

$$\mathcal{Z} = \int \mathcal{D}\phi e^{-S[\phi]} \quad (2.1)$$

where our action is defined in the next section.

2.1.1 The Action

The action for a trapped, rotating, and interacting non-relativistic system in $d + 1$ Euclidean dimensions follows this general formula:

$$S = \int d^d x d\tau [\phi^* (\mathcal{H} - \mu - V_{\text{trap}} - \omega_z L_z) \phi + \lambda(\phi^* \phi)^2]. \quad (2.2)$$

Specifically, in two spatial dimensions, this becomes

$$S = \int dx dy d\tau \left[\phi^* \left(\mathcal{H} - \mu - \frac{m}{2} \omega_{\text{trap}}^2 r_{\perp}^2 - \omega_z L_z \right) \phi + \lambda(\phi^* \phi)^2 \right] \quad (2.3)$$

where $\mathcal{H} = \partial_{\tau} - \frac{\nabla^2}{2m}$ and λ represents a contact interaction coupling. The trapping potential is harmonic, $\omega_{\text{trap}}^2 r_{\perp}^2$ where $r_{\perp}^2 = x^2 + y^2$, and the angular momentum is defined in terms of the quantum mechanical operator, $\omega_z L_z = i\omega_z(x\partial_y - y\partial_x)$. For both the trap and the angular momentum, x and y are measured relative to the origin.

To take this to a lattice representation, we must discretize the space. The origin becomes the center of the lattice, and therefore x and y are measured relative to the point $(N_x/2, N_x/2)$ on the lattice.

Using a backward-difference derivative and denoting the position on the $2 + 1$ dimensional lattice as r , we define: $\partial_j \phi = \frac{1}{a}(\phi_{r-\hat{j}} - \phi_r)$ and $\partial_j^2 \phi = \frac{1}{a^2}(\phi_{r-\hat{j}} - 2\phi_r + \phi_{r+\hat{j}})$. We combine $\partial_{\tau} - \mu$ in the

lattice representation and similarly represent the angular momentum, interaction, and external trap as external gauge fields in order to avoid divergences in the continuum limit (see Appendix A.1 for details and justification of these steps). Finally, using spatial lattice site separation $a = 1$ and temporal lattice spacing $d\tau$, and after scaling our parameters to be dimensionless lattice parameters (again, see Appendix A.1), our lattice action becomes (sum over $r = (x, y, \tau)$ implied):

$$S_{\text{lat}} = \sum_{\vec{x}, \tau} a^d \left[\phi_r^* \phi_r - e^{\bar{\mu}} \phi_r^* \phi_{r-\hat{\tau}} - \frac{1}{2\bar{m}} \sum_{j=1}^d (\phi_r^* \phi_{r-\hat{j}} - 2\phi_r^* \phi_r + \phi_r^* \phi_{r+\hat{j}}) - \frac{\bar{m}}{2} \bar{\omega}_{\text{tr}}^2 \bar{r}_{\perp}^2 \phi_r^* \phi_{r-\hat{\tau}} + i\bar{\omega}_z (\bar{x} \phi_r^* \phi_{r-\hat{y}-\hat{\tau}} - \bar{x} \phi_r^* \phi_{r-\hat{\tau}} - \bar{y} \phi_r^* \phi_{r-\hat{x}-\hat{\tau}} + \bar{y} \phi_r^* \phi_{r-\hat{\tau}}) + \bar{\lambda} (\phi_r^* \phi_{r-\hat{\tau}})^2 \right] \quad (2.4)$$

Note that for $d < 2$, we omit the rotational term, as it requires at least two spatial dimensions. We only consider cases of dimensionality less than two for testing our algorithm against exactly-soluble cases such as the free gas. In addition, going to $d > 2$ would require significant restructuring of the code, so we reserve that for future work.

To simplify our future work, let's write S as a sum of the different contributions to the action:

$$S_{\text{lat}} = (S_{\mu} + S_{\nabla} - S_{\text{trap}} - S_{\omega} + S_{\text{int}}) \quad (2.5)$$

with

$$S_{\mu, r} = \sum_{\vec{x}, \tau} a^d (\phi_r^* \phi_r - e^{\bar{\mu}} \phi_r^* \phi_{r-\hat{\tau}}) \quad (2.6)$$

$$S_{\nabla, r} = \sum_{\vec{x}, \tau} a^d \left(\frac{1}{2\bar{m}} \sum_{j=1}^d (2\phi_r^* \phi_r - \phi_r^* \phi_{r-\hat{j}} - \phi_r^* \phi_{r+\hat{j}}) \right) \quad (2.7)$$

$$S_{\text{trap}, r} = \sum_{\vec{x}, \tau} a^d \left(\frac{\bar{m}}{2} \bar{\omega}_{\text{tr}}^2 \bar{r}_{\perp}^2 \phi_r^* \phi_{r-\hat{\tau}} \right) \quad (2.8)$$

$$S_{\omega, r} = \sum_{\vec{x}, \tau} a^d (i\bar{\omega}_z (\bar{x} \phi_r^* \phi_{r-\hat{\tau}} - \bar{x} \phi_r^* \phi_{r-\hat{y}-\hat{\tau}} - \bar{y} \phi_r^* \phi_{r-\hat{\tau}} + \bar{y} \phi_r^* \phi_{r-\hat{x}-\hat{\tau}})) \quad (2.9)$$

$$S_{\text{int}, r} = \sum_{\vec{x}, \tau} a^d (\bar{\lambda} (\phi_r^* \phi_{r-\hat{\tau}})^2). \quad (2.10)$$

From here on, we will be working with these individual contributions to the action.

2.2 The Langevin Equations

In order to treat this action composed of complex-valued fields, we use a method called complex Langevin (CL). This method uses a stochastic evolution of the complex fields in a fictitious time – Langevin time – in order to produce sets of solutions distributed according to the weight e^{-S} . Just as standard Monte Carlo methods operate by sampling from the distribution e^{-S} , this method allows us to stochastically evaluate observables whose physical behavior is governed by our action, S .

First, we must write our complex fields as a complex sum of two real fields (i.e. $\phi = \frac{1}{\sqrt{2}} (\phi_1 + i\phi_2)$). This is worked out in Appendix A.2 for all the contributions to our action. We then complexify the real fields and evolve the four resulting components ($\phi_1^R, \phi_1^I, \phi_2^R$, and ϕ_2^I) according to the complex

Langevin equations, a set of coupled stochastic differential equations shown here:

$$\phi_{a,r}^R(n+1) = \phi_{a,r}^R(n) + \epsilon K_{a,r}^R(n) + \sqrt{\epsilon} \eta_{a,r}(n) \quad (2.11)$$

$$\phi_{a,r}^I(n+1) = \phi_{a,r}^I(n) + \epsilon K_{a,r}^I(n), \quad (2.12)$$

where $a = 1, 2$ labels our two real fields, η is Gaussian-distributed real noise with mean of 0 and standard deviation of $\sqrt{2}$. The drift functions, K , are derived from the action:

$$K_{a,r}^R = -\text{Re} \left[\frac{\delta S}{\delta \phi_{a,r}} \Big|_{\phi_a \rightarrow \phi_a^R + i\phi_a^I} \right] \quad (2.13)$$

$$K_{a,r}^I = -\text{Im} \left[\frac{\delta S}{\delta \phi_{a,r}} \Big|_{\phi_a \rightarrow \phi_a^R + i\phi_a^I} \right] \quad (2.14)$$

The derivation of the Langevin equations is worked out in Appendix A.3, and the results are shown below with the sums over a and b implied:

$$\begin{aligned} -K_{a,r}^R &= \phi_{a,r}^R - \frac{e^{d\tau\mu}}{2} (\phi_{a,r-\hat{\tau}}^R + \phi_{a,r+\hat{\tau}}^R) + \frac{e^{d\tau\mu}}{2} \epsilon_{ab} (\phi_{b,r-\hat{\tau}}^I - \phi_{b,r+\hat{\tau}}^I) \\ &\quad + \frac{d\tau}{2m} \left(2d\phi_{a,r}^R - \sum_{i=\pm 1}^d \phi_{a,r+\hat{i}}^R \right) \\ &\quad - \frac{d\tau\omega_{\text{tr}}^2(r_{\perp}^2)}{4} ((\phi_{a,r+\hat{\tau}}^R + \phi_{a,r-\hat{\tau}}^R) - \epsilon_{ab} (\phi_{b,r+\hat{\tau}}^I + \phi_{b,r-\hat{\tau}}^I)) \\ &\quad - \frac{d\tau\omega_z}{2} [\epsilon_{ab} [x(\phi_{b,r-\hat{y}}^R - \phi_{b,r+\hat{y}}^R) - y(\phi_{b,r-\hat{x}}^R - \phi_{b,r+\hat{x}}^R)] - 2(x-y)\phi_{a,r}^I] \\ &\quad - \frac{\omega_z}{2} [x(\phi_{a,r-\hat{y}}^I + \phi_{a,r+\hat{y}}^I) - y(\phi_{a,r-\hat{x}}^I + \phi_{a,r+\hat{x}}^I)] \\ &\quad + d\tau\lambda [\phi_{a,r}^R(\phi_{b,r}^R)^2 - \phi_{a,r}^R(\phi_{b,r}^I)^2 - 2\phi_{a,r}^I\phi_{b,r}^R\phi_{b,r}^I] \end{aligned} \quad (2.15)$$

$$\begin{aligned} -K_{a,r}^I &= \phi_{a,r}^I - \frac{e^{d\tau\mu}}{2} (\phi_{a,r-\hat{\tau}}^I + \phi_{a,r+\hat{\tau}}^I) - \frac{e^{d\tau\mu}}{2} \epsilon_{ab} (\phi_{b,r-\hat{\tau}}^R - \phi_{b,r+\hat{\tau}}^R) \\ &\quad + \frac{d\tau}{2m} \left(2d\phi_{a,r}^I - \sum_{i=\pm 1}^d \phi_{a,r+\hat{i}}^I \right) \\ &\quad - \frac{d\tau\omega_{\text{tr}}^2(r_{\perp}^2)}{4} ((\phi_{a,r+\hat{\tau}}^I + \phi_{a,r-\hat{\tau}}^I) + \epsilon_{ab}(\phi_{b,r+\hat{\tau}}^R + \phi_{b,r-\hat{\tau}}^R)) \\ &\quad - \frac{d\tau\omega_z}{2} [\epsilon_{ab} (x(\phi_{b,r-\hat{y}}^I - \phi_{b,r+\hat{y}}^I) - y(\phi_{b,r-\hat{x}}^I - \phi_{b,r+\hat{x}}^I)) + 2(x-y)\phi_{a,r}^R] \\ &\quad - \frac{\omega_z}{2} [y(\phi_{a,r-\hat{x}}^R + \phi_{a,r+\hat{x}}^R) - x(\phi_{a,r-\hat{y}}^R + \phi_{a,r+\hat{y}}^R)] \\ &\quad + d\tau\lambda [\phi_{a,r}^I(\phi_{b,r}^R)^2 + 2\phi_{a,r}^R\phi_{b,r}^R\phi_{b,r}^I - \phi_{a,r}^I(\phi_{b,r}^I)^2] \end{aligned} \quad (2.16)$$

This evolution is repeated until we have evolved for a long period in Langevin time (determined by the observation of thermalization followed by enough steps to produce good statistical error). Observables of interest can be calculated as functions of the fields at each point in Langevin time and averaged to find the expectation value.

2.3 Observables

2.3.1 Observables averaged over the volume

The observables of interest in this simulation are the density $\langle \hat{n} \rangle$, the field modulus $\langle \phi^2 \phi \rangle$, the angular momentum $\langle \hat{L}_z \rangle$, the moment of inertia $\langle \hat{I}_z \rangle$, and the circulation of the fields around the center of the lattice. The individual contributions to the energy (kinetic, trapping potential, and interaction potential) have also been derived, and can be found in Appendix A.4.

The sum over all lattice sites and subsequent normalization by the lattice volume $V = N_x^d N_\tau$ is implied:

$$\text{Re}\langle n \rangle = \frac{e^{\bar{\mu}}}{2} \sum_{a,b=1}^2 [\delta_{ab}(\phi_{a,r}^R \phi_{r,b-\hat{\tau}}^R - \phi_{a,r}^I \phi_{r,b-\hat{\tau}}^I) - \epsilon_{ab}(\phi_{a,r}^R \phi_{r,b-\hat{\tau}}^I + \phi_{a,r}^I \phi_{r,b-\hat{\tau}}^R)] \quad (2.17)$$

$$\text{Im}\langle n \rangle = \frac{e^{\bar{\mu}}}{2} \sum_{a,b=1}^2 [\delta_{ab}(\phi_{a,r}^R \phi_{r,b-\hat{\tau}}^I + \phi_{a,r}^I \phi_{r,b-\hat{\tau}}^R) + \epsilon_{ab}(\phi_{a,r}^R \phi_{r,b-\hat{\tau}}^R - \phi_{a,r}^I \phi_{r,b-\hat{\tau}}^I)] \quad (2.18)$$

$$\text{Re}\langle \phi^* \phi \rangle = \frac{1}{2} \sum_{a=1}^2 (\phi_{a,r}^R \phi_{a,r}^R - \phi_{a,r}^I \phi_{a,r}^I) \quad (2.19)$$

$$\text{Im}\langle \phi^* \phi \rangle = \sum_{a=1}^2 \phi_{a,r}^R \phi_{a,r}^I \quad (2.20)$$

$$\begin{aligned} \text{Re}\langle L_z \rangle = & \frac{1}{2} \sum_{a=1}^2 [(y-x)\phi_{a,r}^R \phi_{a,r-\hat{\tau}}^I + (y-x)\phi_{a,r}^I \phi_{a,r-\hat{\tau}}^R \\ & + x\phi_{a,r}^R \phi_{a,r-\hat{\tau}-\hat{y}}^I + x\phi_{a,r}^I \phi_{a,r-\hat{\tau}-\hat{y}}^R - y\phi_{a,r}^R \phi_{a,r-\hat{\tau}-\hat{x}}^I - y\phi_{a,r}^I \phi_{a,r-\hat{\tau}-\hat{x}}^R \\ & + \epsilon_{ab} \sum_{b=1}^2 ((x-y)\phi_{a,r}^I \phi_{b,r-\hat{\tau}-\hat{y}}^I + (y-x)\phi_{a,r}^R \phi_{b,r-\hat{\tau}-\hat{y}}^R \\ & + x\phi_{a,r}^R \phi_{b,r-\hat{\tau}-\hat{y}}^R - x\phi_{a,r}^I \phi_{b,r-\hat{\tau}-\hat{y}}^I + y\phi_{a,r}^I \phi_{b,r-\hat{\tau}-\hat{x}}^I - y\phi_{a,r}^R \phi_{b,r-\hat{\tau}-\hat{x}}^R)] \end{aligned} \quad (2.21)$$

$$\begin{aligned} \text{Im}\langle L_z \rangle = & \frac{1}{2} \sum_{a=1}^2 [(x-y)\phi_{a,r}^R \phi_{a,r-\hat{\tau}}^R + (y-x)\phi_{a,r}^I \phi_{a,r-\hat{\tau}}^I - x\phi_{a,r}^R \phi_{a,r-\hat{\tau}-\hat{y}}^R \\ & + x\phi_{a,r}^I \phi_{a,r-\hat{\tau}-\hat{y}}^I + y\phi_{a,r}^R \phi_{a,r-\hat{\tau}-\hat{x}}^R - y\phi_{a,r}^I \phi_{a,r-\hat{\tau}-\hat{x}}^I \\ & + \epsilon_{ab} \sum_{b=1}^2 ((y-x)\phi_{a,r}^R \phi_{b,r-\hat{\tau}}^I + (y-x)\phi_{a,r}^I \phi_{b,r-\hat{\tau}}^R + x\phi_{a,r}^R \phi_{b,r-\hat{\tau}-\hat{y}}^I \\ & + x\phi_{a,r}^I \phi_{b,r-\hat{\tau}-\hat{y}}^R - y\phi_{a,r}^R \phi_{b,r-\hat{\tau}-\hat{x}}^I - y\phi_{a,r}^I \phi_{b,r-\hat{\tau}-\hat{x}}^R)] \end{aligned} \quad (2.22)$$

The moment of inertia can be calculated from this by differentiating with respect to the angular frequency. We can do this by taking a numerical gradient.

The circulation is computed along an $l \times l$ loop on the lattice:

$$\Gamma[l] = \frac{1}{2\pi} \sum_{l \times l} (\theta_{t,x+j} - \theta_{t,x}) \quad (2.23)$$

where

$$\theta_{t,x} = \tan^{-1} \left(\frac{\phi_{1,t,x}^I + \phi_{2,t,x}^R}{\phi_{1,t,x}^R - \phi_{2,t,x}^I} \right) \quad (2.24)$$

and $\theta_{t,x+j}$ is computed at the next site on the loop from $\theta_{t,x}$ for each point along the loop.
See Appendix A.4 for the full derivation of the observables.

2.3.2 Observables per site

The next phase of this project will move to larger lattices in order to calculate the density profiles of the rotating system. We expect to see the formation of vortices in the density of the fluid (localized sites of 0 density). We expect these vortices to be concentrated closer to the center of the trap. In order to observe these vortices and their structure, we need a finer lattice mesh in the center of the system. This will involve a great deal more computational intensity.

Appendices

Appendix A

NRRB Derivations

A.1 Justification for the Form of the Non-Relativistic Lattice Action

The continuum action for bosons with a non-relativistic dispersion, a rotating external potential, a non-zero chemical potential, an external trap potential, and an interaction term is as follows:

$$S = \int_V \phi^* \left(\partial_\tau - \frac{1}{2m} \nabla^2 - \mu - i\omega_z(x\partial_y - y\partial_x) - \frac{m\omega_{\text{trap}}^2}{2}(x^2 + y^2) \right) \phi + \lambda \int_V (\phi^* \phi)^2. \quad (\text{A.1})$$

To convert this to a lattice action, we must first discretize the derivatives. We will use a backwards finite difference discretization for the single derivative and a central difference approximation for the double derivative, such that:

$$\partial_i \phi_r = \frac{1}{a} (\phi_r - \phi_{r-\hat{i}}) \quad (\text{A.2})$$

$$\nabla^2 \phi_r = \sum_i \frac{1}{a^2} (\phi_{r+\hat{i}} - 2\phi_r + \phi_{r-\hat{i}}), \quad (\text{A.3})$$

where $r = (x, y, \tau)$ and the discretization length is a for spatial derivatives and $d\tau$ for temporal ones.

In order to treat the finite chemical potential, the external trapping potential, the rotation, and the interaction we must shift our indices on the field that is acted on by these external parameters by one step in the time direction. This is to make these potentials gauge invariant in the lattice formulation. Since we have periodic boundary conditions in time, we don't have to worry about boundaries in time.

When we go from the continuous action to the discrete action, we must account for the role of finite spacing.

$$\int d^d x d\tau \rightarrow \sum_{\vec{x}, \tau} a^d d\tau. \quad (\text{A.4})$$

We then scale our parameters to their lattice versions, incorporating the lattice spacing, denoted

by a bar:

$$\begin{aligned}
\bar{x} &= x/a \\
\bar{y} &= y/a \\
\bar{r}^2 &= r^2/a^2 \\
\bar{\mu} &= d\tau\mu \\
\bar{m} &= ma^2/d\tau \\
\bar{\omega}_{\text{tr}} &= d\tau\omega_{\text{tr}} \\
\bar{\omega}_z &= d\tau\omega_z \\
\bar{\lambda} &= d\tau\lambda
\end{aligned}$$

This allows us to cancel factors of $d\tau$ and leaves us with an overall a^d that we can divide out. Therefore, our lattice action becomes:

$$\begin{aligned}
S_{\text{lat}} = \sum_{\vec{x}, \tau} a^d & \left[\phi_r^* \phi_r - \phi_r^* \phi_{r-\hat{\tau}} - \bar{\mu} \phi_r^* \phi_{r-\hat{\tau}} - \frac{1}{2\bar{m}} \sum_{j=1}^d (\phi_r^* \phi_{r-\hat{j}} - 2\phi_r^* \phi_r + \phi_r^* \phi_{r+\hat{j}}) \right. \\
& - \frac{\bar{m}}{2} \bar{\omega}_{\text{tr}}^2 \bar{r}_{\perp}^2 \phi_r^* \phi_{r-\hat{\tau}} + i\bar{\omega}_z (\bar{x} \phi_r^* \phi_{r-\hat{y}-\hat{\tau}} - \bar{x} \phi_r^* \phi_{r-\hat{\tau}} - \bar{y} \phi_r^* \phi_{r-\hat{x}-\hat{\tau}} + \bar{y} \phi_r^* \phi_{r-\hat{\tau}}) \\
& \left. + \bar{\lambda} (\phi_r^* \phi_{r-\hat{\tau}})^2 \right] \tag{A.5}
\end{aligned}$$

We can then combine our time derivative and our chemical potential in the following way:

$$\begin{aligned}
S_{\text{lat}} = \sum_{\vec{x}, \tau} a^d & \left[\phi_r^* \phi_r - (1 + \bar{\mu}) \phi_r^* \phi_{r-\hat{\tau}} - \frac{1}{2\bar{m}} \sum_{j=1}^d (\phi_r^* \phi_{r-\hat{j}} - 2\phi_r^* \phi_r + \phi_r^* \phi_{r+\hat{j}}) \right. \\
& - \frac{\bar{m}}{2} \bar{\omega}_{\text{tr}}^2 \bar{r}_{\perp}^2 \phi_r^* \phi_{r-\hat{\tau}} + i\bar{\omega}_z (\bar{x} \phi_r^* \phi_{r-\hat{y}-\hat{\tau}} - \bar{x} \phi_r^* \phi_{r-\hat{\tau}} - \bar{y} \phi_r^* \phi_{r-\hat{x}-\hat{\tau}} + \bar{y} \phi_r^* \phi_{r-\hat{\tau}}) \\
& \left. + \bar{\lambda} (\phi_r^* \phi_{r-\hat{\tau}})^2 \right] \tag{A.6}
\end{aligned}$$

Note that to second order in the lattice size, this is equivalent to:

$$\begin{aligned}
S_{\text{lat}} = \sum_{\vec{x}, \tau} a^d & \left[\phi_r^* \phi_r - e^{\bar{\mu}} \phi_r^* \phi_{r-\hat{\tau}} - \frac{1}{2\bar{m}} \sum_{j=1}^d (\phi_r^* \phi_{r-\hat{j}} - 2\phi_r^* \phi_r + \phi_r^* \phi_{r+\hat{j}}) - \frac{\bar{m}}{2} \bar{\omega}_{\text{tr}}^2 \bar{r}_{\perp}^2 \phi_r^* \phi_{r-\hat{\tau}} \right. \\
& \left. + i\bar{\omega}_z (\bar{x} \phi_r^* \phi_{r-\hat{y}-\hat{\tau}} - \bar{x} \phi_r^* \phi_{r-\hat{\tau}} - \bar{y} \phi_r^* \phi_{r-\hat{x}-\hat{\tau}} + \bar{y} \phi_r^* \phi_{r-\hat{\tau}}) + \bar{\lambda} (\phi_r^* \phi_{r-\hat{\tau}})^2 \right] \tag{A.7}
\end{aligned}$$

This will be our lattice action, which we will complexify and use to evolve our system in Langevin time. To simplify, let's divide the lattice action into smaller components:

$$S_{\text{lat}} = (S_{\mu} + S_{\nabla} - S_{\text{trap}} - S_{\omega} + S_{\text{int}}) \tag{A.8}$$

with

$$S_{\mu,r} = \sum_{\vec{x},\tau} a^d (\phi_r^* \phi_r - e^{\bar{\mu}} \phi_r^* \phi_{r-\hat{\tau}}) \quad (\text{A.9})$$

$$S_{\nabla,r} = \sum_{\vec{x},\tau} a^d \left(\frac{1}{2\bar{m}} \sum_{j=1}^d (2\phi_r^* \phi_r - \phi_r^* \phi_{r-\hat{j}} - \phi_r^* \phi_{r+\hat{j}}) \right) \quad (\text{A.10})$$

$$S_{\text{trap},r} = \sum_{\vec{x},\tau} a^d \left(\frac{\bar{m}}{2} \bar{\omega}_{\text{tr}}^2 \bar{r}_{\perp}^2 \phi_r^* \phi_{r-\hat{\tau}} \right) \quad (\text{A.11})$$

$$S_{\omega,r} = \sum_{\vec{x},\tau} a^d (i\bar{\omega}_z (\bar{x} \phi_r^* \phi_{r-\hat{\tau}} - \bar{x} \phi_r^* \phi_{r-\hat{y}-\hat{\tau}} - \bar{y} \phi_r^* \phi_{r-\hat{\tau}} + \bar{y} \phi_r^* \phi_{r-\hat{x}-\hat{\tau}})) \quad (\text{A.12})$$

$$S_{\text{int},r} = \sum_{\vec{x},\tau} a^d (\bar{\lambda} (\phi_r^* \phi_{r-\hat{\tau}})^2). \quad (\text{A.13})$$

Note that we are restricting ourselves to two spatial dimensions at this point in the work. The extension of this method to three-dimensional rotating systems is saved for future work.

A.2 Writing the Complex Action in Terms of Real Fields

This action must first be rewritten with the complex fields expressed in terms of two real fields, $\phi = \frac{1}{\sqrt{2}} (\phi_1 + i\phi_2)$ and $\phi^* = \frac{1}{\sqrt{2}} (\phi_1 - i\phi_2)$. Each piece of the action is computed below. Note from this point on, we drop the external sum over the entire spacetime lattice and its weighting (a^d), as it is the same for all components of the action.

First, the time derivative and chemical potential part of the action at any given site \vec{x}, τ on the lattice:

$$\begin{aligned} S_{\mu,r} &= \phi_r^* \phi_r - e^{\bar{\mu}} \phi_r^* \phi_{r-\hat{\tau}} \\ &= \frac{1}{2} [\phi_{1,r}^2 + \phi_{2,r}^2 - e^{\bar{\mu}} (\phi_{1,r} \phi_{1,r-\hat{\tau}} + i\phi_{1,r} \phi_{2,r-\hat{\tau}} - i\phi_{2,r} \phi_{1,r-\hat{\tau}} + \phi_{2,r} \phi_{2,r-\hat{\tau}})] \\ &= \frac{1}{2} \sum_{a=1}^2 \left[\phi_{a,r}^2 - e^{\bar{\mu}} \phi_{a,r} \phi_{a,r-\hat{\tau}} - i e^{\bar{\mu}} \sum_{b=1}^2 \epsilon_{ab} \phi_{a,r} \phi_{b,r-\hat{\tau}} \right], \end{aligned} \quad (\text{A.14})$$

where $\epsilon_{12} = 1$, $\epsilon_{21} = -1$, $\epsilon_{11} = \epsilon_{22} = 0$. Next, the spatial derivative part (corresponding to the kinetic energy):

$$\begin{aligned} S_{\nabla,r} &= \frac{1}{2\bar{m}} \sum_{j=1}^d (2\phi_r^* \phi_r - \phi_r^* \phi_{r-\hat{j}} - \phi_r^* \phi_{r+\hat{j}}) \\ &= \frac{1}{4\bar{m}} \sum_{j=1}^d [2(\phi_{1,r}^2 + \phi_{2,r}^2) - (\phi_{1,r} \phi_{1,r+\hat{i}} + i\phi_{1,r} \phi_{2,r+\hat{i}} - i\phi_{2,r} \phi_{1,r+\hat{i}} + \phi_{2,r} \phi_{2,r+\hat{i}}) \\ &\quad - (\phi_{1,r} \phi_{1,r-\hat{i}} + i\phi_{1,r} \phi_{2,r-\hat{i}} - i\phi_{2,r} \phi_{1,r-\hat{i}} + \phi_{2,r} \phi_{2,r-\hat{i}})] \\ &= \frac{1}{4\bar{m}} \sum_{j=1}^d \sum_{a=1}^2 \left[2\phi_{a,r}^2 - (\phi_a \phi_{a,r-\hat{j}} + \phi_a \phi_{a,r+\hat{j}}) - i \sum_{b=1}^2 \epsilon_{ab} (\phi_{a,r} \phi_{b,r-\hat{j}} + \phi_{a,r} \phi_{b,r+\hat{j}}) \right] \end{aligned} \quad (\text{A.15})$$

Then, for the part of the action due to the external trapping potential:

$$\begin{aligned}
S_{\text{trap},r} &= \frac{\bar{m}}{2} \bar{\omega}_{\text{tr}}^2 \bar{r}_{\perp}^2 \phi_r^* \phi_{r-\hat{\tau}} \\
&= \frac{\bar{m}}{4} \bar{\omega}_{\text{tr}}^2 \bar{r}_{\perp}^2 [\phi_{1,r} \phi_{1,r-\tau} + i \phi_{1,r} \phi_{2,r-\tau} - i \phi_{2,r} \phi_{1,r-\tau} + \phi_{2,r} \phi_{2,r-\tau}] \\
&= \frac{\bar{m}}{4} \bar{\omega}_{\text{tr}}^2 \bar{r}_{\perp}^2 \sum_{a=1}^2 \left[\phi_{a,r} \phi_{a,r-\hat{\tau}} + i \sum_{b=1}^2 \epsilon_{ab} \phi_{a,r} \phi_{b,r-\hat{\tau}} \right].
\end{aligned} \tag{A.16}$$

Next, the rotational piece:

$$\begin{aligned}
S_{\omega,r} &= i \bar{\omega}_z (\bar{x} \phi_r^* \phi_{r-\hat{\tau}} - \bar{x} \phi_r^* \phi_{r-\hat{y}-\hat{\tau}} - \bar{y} \phi_r^* \phi_{r-\hat{\tau}} + \bar{y} \phi_r^* \phi_{r-\hat{x}-\hat{\tau}}) \\
&= \frac{\bar{\omega}_z}{2} [(\bar{y} - \bar{x}) (\phi_{1,r} \phi_{2,r-\hat{\tau}} - \phi_{2,r} \phi_{1,r-\hat{\tau}}) + \bar{x} (\phi_{1,r} \phi_{2,r-\hat{y}-\hat{\tau}} - \phi_{2,r} \phi_{1,r-\hat{y}-\hat{\tau}}) \\
&\quad - \bar{y} (\phi_{1,r} \phi_{2,r-\hat{x}-\hat{\tau}} - \phi_{2,r} \phi_{1,r-\hat{x}-\hat{\tau}})] \\
&\quad + i \frac{\bar{\omega}_z}{2} [(\bar{x} - \bar{y}) (\phi_{1,r} \phi_{1,r-\hat{\tau}} + \phi_{2,r} \phi_{2,r-\hat{\tau}}) - \bar{x} (\phi_{1,r} \phi_{1,r-\hat{y}-\hat{\tau}} + \phi_{2,r} \phi_{2,r-\hat{y}-\hat{\tau}}) \\
&\quad + \bar{y} (\phi_{1,r} \phi_{1,r-\hat{x}-\hat{\tau}} + \phi_{2,r} \phi_{2,r-\hat{x}-\hat{\tau}})] \\
&= \frac{\bar{\omega}_z}{2} \sum_{a=1}^2 \left[\sum_{b=1}^2 \epsilon_{ab} ((\bar{y} - \bar{x}) \phi_{a,r} \phi_{b,r-\hat{\tau}} + \bar{x} \phi_{a,r} \phi_{b,r-\hat{y}-\hat{\tau}} - \bar{y} \phi_{a,r} \phi_{b,r-\hat{x}-\hat{\tau}}) \right] \\
&\quad + i \frac{\bar{\omega}_z}{2} \sum_{a=1}^2 [(\bar{x} - \bar{y}) \phi_{a,r} \phi_{a,r-\hat{\tau}} - \bar{x} \phi_{a,r} \phi_{a,r-\hat{y}-\hat{\tau}} + \bar{y} \phi_{a,r} \phi_{a,r-\hat{x}-\hat{\tau}}]
\end{aligned} \tag{A.17}$$

And finally, the interaction term in the action:

$$\begin{aligned}
S_{\text{int},r} &= \bar{\lambda} (\phi_r^* \phi_{r-\hat{\tau}})^2 \\
&= \frac{\bar{\lambda}}{4} [\phi_{1,r}^2 \phi_{1,r-\hat{\tau}}^2 + \phi_{2,r}^2 \phi_{2,r-\hat{\tau}}^2 + 4 \phi_{1,r} \phi_{2,r} \phi_{1,r-\hat{\tau}} \phi_{2,r-\hat{\tau}} - \phi_{1,r}^2 \phi_{2,r-\hat{\tau}}^2 - \phi_{2,r}^2 \phi_{1,r-\hat{\tau}}^2] \\
&\quad + i \frac{\bar{\lambda}}{4} [2 \phi_{1,r}^2 \phi_{1,r-\hat{\tau}} \phi_{2,r-\hat{\tau}} - 2 \phi_{2,r}^2 \phi_{1,r-\hat{\tau}} \phi_{2,r-\hat{\tau}} - 2 \phi_{1,r} \phi_{2,r} \phi_{1,r-\hat{\tau}}^2 + 2 \phi_{1,r} \phi_{2,r} \phi_{2,r-\hat{\tau}}^2] \\
&= \frac{\bar{\lambda}}{4} \sum_{a=1}^2 \sum_{b=1}^2 [2 \phi_{a,r} \phi_{a,r-\hat{\tau}} \phi_{b,r} \phi_{b,r-\hat{\tau}} - \phi_{a,r}^2 \phi_{b,r-\hat{\tau}}^2] \\
&\quad + i \frac{\bar{\lambda}}{2} \sum_{a=1}^2 \sum_{b=1}^2 [\epsilon_{ab} (\phi_{a,r}^2 \phi_{a,r-\hat{\tau}} \phi_{b,r-\hat{\tau}} - \phi_{a,r} \phi_{b,r} \phi_{a,r-\hat{\tau}}^2)].
\end{aligned}$$

We will work with the lattice action in this form in order to derive the Langevin drift function.

A.3 Generating the NRRB CL Equations

A.3.1 Derivatives on the Lattice

When taking derivatives of this lattice action with respect to the fields, we do the following:

$$\begin{aligned}
\frac{\delta}{\delta\phi_{c,r}} \left(\sum_{q=1}^{N_r} \sum_{a=1}^2 \phi_{a,q} \phi_{a,q+\hat{i}} \right) &= \sum_{a=1}^2 \sum_{q=1}^{N_r} \left(\phi_{a,q} \frac{\delta}{\delta\phi_{c,r}} \phi_{a,q+\hat{i}} + \frac{\delta\phi_{a,q}}{\delta\phi_{c,r}} \phi_{a,q+\hat{i}} \right) \\
&= \sum_{a=1}^2 \sum_{q=1}^{N_r} (\phi_{a,q} \delta_{c,a} \delta_{r,q+\hat{i}} + \delta_{c,a} \delta_{q,r} \phi_{a,q+\hat{i}}) \\
&= \phi_{c,r-\hat{i}} + \phi_{c,r+\hat{i}}.
\end{aligned} \tag{A.18}$$

Similarly,

$$\frac{\delta}{\delta\phi_{c,r}} \left(\sum_{q=1}^{N_r} \sum_{a=1}^2 \sum_{b=1}^2 \epsilon_{ab} \phi_{a,q} \phi_{b,q+\hat{i}} \right) = \sum_{b=1}^2 \epsilon_{cb} (\phi_{b,r-\hat{i}} + \phi_{b,r+\hat{i}}). \tag{A.19}$$

A.3.2 Computing the derivative of the action with respect to the real fields

The first step in computing the CL Equations is to find $\frac{\delta S_r}{\delta\phi_{a,r}}$. This is done below, with the sum over $a = 1, 2$ implied:

$$\frac{\delta S_r}{\delta\phi_{a,r}} = \frac{\delta S_{\mu,r}}{\delta\phi_{a,r}} + \frac{\delta S_{\nabla,r}}{\delta\phi_{a,r}} - \frac{\delta S_{\text{trap},r}}{\delta\phi_{a,r}} - \frac{\delta S_{\omega,r}}{\delta\phi_{a,r}} + \frac{\delta S_{\text{int},r}}{\delta\phi_{a,r}} \tag{A.20}$$

Again, we proceed by modifying each of the 5 parts of the action. First, the time and chemical potential term:

$$\begin{aligned}
\frac{\delta}{\delta\phi_{a,r}} S_{\mu,r} &= \frac{1}{2} \frac{\delta}{\delta\phi_{a,r}} \sum_{c=1}^2 \left[\phi_{c,r}^2 - e^{\bar{\mu}} \phi_{c,r} \phi_{c,r-\hat{\tau}} - i e^{\bar{\mu}} \sum_{b=1}^2 \epsilon_{cb} \phi_{c,r} \phi_{b,r-\hat{\tau}} \right] \\
&= \phi_{a,r} - \frac{1}{2} e^{\bar{\mu}} (\phi_{a,r-\hat{\tau}} + \phi_{a,r+\hat{\tau}}) - \frac{i}{2} e^{\bar{\mu}} \epsilon_{ab} (\phi_{b,r-\hat{\tau}} + \phi_{b,r+\hat{\tau}})
\end{aligned} \tag{A.21}$$

Next, the spatial derivative part:

$$\begin{aligned}
\frac{\delta}{\delta\phi_{a,r}} S_{\nabla,r} &= \frac{1}{4\bar{m}} \frac{\delta}{\delta\phi_{a,r}} \sum_{j=1}^d \sum_{c=1}^2 \left[2\phi_{c,r}^2 - (\phi_{c,r} \phi_{c,r+\hat{j}} + \phi_{c,r} \phi_{c,r-\hat{j}}) \right. \\
&\quad \left. - i \sum_{b=1}^2 \epsilon_{cb} (\phi_{c,r} \phi_{b,r+\hat{j}} + \phi_{c,r} \phi_{b,r-\hat{j}}) \right] \\
&= \frac{1}{4\bar{m}} \sum_{j=1}^d \left[4\phi_{a,r} - 2(\phi_{a,r+\hat{j}} + \phi_{a,r-\hat{j}}) - 2i \sum_{b=1}^2 \epsilon_{ab} (\phi_{b,r+\hat{j}} + \phi_{b,r-\hat{j}}) \right] \\
&= \frac{1}{2\bar{m}} \sum_{j=1}^d \left[2\phi_{a,r} - (\phi_{a,r+\hat{j}} + \phi_{a,r-\hat{j}}) - i \sum_{b=1}^2 \epsilon_{ab} (\phi_{b,r+\hat{j}} + \phi_{b,r-\hat{j}}) \right]
\end{aligned} \tag{A.22}$$

Then the part of the action due to the external trapping potential:

$$\begin{aligned}
\frac{\delta}{\delta\phi_{a,r}} S_{\text{trap},r} &= \frac{\bar{m}\bar{\omega}_{\text{tr}}^2 \bar{r}_{\perp}^2}{4} \frac{\delta}{\delta\phi_{a,r}} \sum_{c=1}^2 \left(\phi_{c,r} \phi_{c,r-\hat{\tau}} + i \sum_{b=1}^2 \epsilon_{cb} \phi_{c,r} \phi_{b,r-\hat{\tau}} \right) \\
&= \frac{\bar{m}\bar{\omega}_{\text{tr}}^2 \bar{r}_{\perp}^2}{4} \left(\phi_{a,r-\hat{\tau}} + \phi_{a,r+\hat{\tau}} + i \sum_{b=1}^2 \epsilon_{ab} (\phi_{b,r-\hat{\tau}} + \phi_{b,r+\hat{\tau}}) \right)
\end{aligned}$$

where $\bar{r}_\perp^2 = \bar{x}^2 + \bar{y}^2$, or in 1d, $\bar{r}_\perp^2 = \bar{x}^2$. Next, the rotational piece:

$$\begin{aligned}
\frac{\delta}{\delta\phi_{a,r}} S_{\omega,r} &= \frac{\bar{\omega}_z}{2} \frac{\delta}{\delta\phi_{a,r}} \sum_{c=1}^2 \left[\sum_{b=1}^2 \epsilon_{cb} ((\bar{y} - \bar{x})\phi_{c,r}\phi_{b,r-\hat{\tau}} + \bar{x}\phi_{c,r}\phi_{b,r-\hat{y}-\hat{\tau}} - \bar{y}\phi_{c,r}\phi_{b,r-\hat{x}-\hat{\tau}}) \right. \\
&\quad \left. + i((\bar{x} - \bar{y})\phi_{c,r}\phi_{c,r-\hat{\tau}} - \bar{x}\phi_{c,r}\phi_{c,r-\hat{y}-\hat{\tau}} + \bar{y}\phi_{c,r}\phi_{c,r-\hat{x}-\hat{\tau}}) \right] \\
&= \frac{\bar{\omega}_z}{2} \left[\sum_{b=1}^2 \epsilon_{ab} ((\bar{y} - \bar{x})(\phi_{b,r-\hat{\tau}} + \phi_{b,r+\hat{\tau}}) + \bar{x}(\phi_{b,r-\hat{y}-\hat{\tau}} + \phi_{b,r+\hat{y}+\hat{\tau}}) \right. \\
&\quad \left. - \bar{y}(\phi_{b,r-\hat{x}-\hat{\tau}} + \phi_{b,r+\hat{x}+\hat{\tau}})) + i((\bar{x} - \bar{y})(\phi_{a,r-\hat{\tau}} + \phi_{a,r+\hat{\tau}}) \right. \\
&\quad \left. - \bar{x}(\phi_{a,r-\hat{y}-\hat{\tau}} + \phi_{a,r+\hat{y}+\hat{\tau}}) + \bar{y}(\phi_{a,r-\hat{x}-\hat{\tau}} + \phi_{a,r+\hat{x}+\hat{\tau}})) \right] \quad (\text{A.23})
\end{aligned}$$

Note, this term is set to zero unless $d > 1$. And finally, the interaction term in the action:

$$\begin{aligned}
\frac{\delta}{\delta\phi_{a,r}} S_{\text{int},r} &= \frac{\bar{\lambda}}{4} \frac{\delta}{\delta\phi_{a,r}} \sum_{c=1}^2 \sum_{b=1}^2 [2\phi_{c,r}\phi_{c,r-\hat{\tau}}\phi_{b,r}\phi_{b,r-\hat{\tau}} - \phi_{c,r}^2\phi_{b,r-\hat{\tau}}^2 \\
&\quad + 2i\epsilon_{cb}(\phi_{c,r}^2\phi_{c,r-\hat{\tau}}\phi_{b,r-\hat{\tau}} - \phi_{c,r}\phi_{b,r}\phi_{c,r-\hat{\tau}}^2)] \\
&= \frac{\bar{\lambda}}{4} \sum_{b=1}^2 [4\phi_{b,r}(\phi_{a,r+\hat{\tau}}\phi_{b,r+\hat{\tau}} + \phi_{a,r-\hat{\tau}}\phi_{b,r-\hat{\tau}}) - 2\phi_{a,r}(\phi_{b,r+\hat{\tau}}^2 + \phi_{b,r-\hat{\tau}}^2) \\
&\quad + 2i\epsilon_{ab}(\phi_{b,r}(\phi_{a,r+\hat{\tau}}^2 + \phi_{a,r-\hat{\tau}}^2) - \phi_{b,r}(\phi_{b,r+\hat{\tau}}^2 + \phi_{b,r-\hat{\tau}}^2) + 2\phi_{a,r}(\phi_{a,r-\hat{\tau}}\phi_{b,r-\hat{\tau}} + \phi_{a,r+\hat{\tau}}\phi_{b,r+\hat{\tau}}))] \quad (\text{A.24})
\end{aligned}$$

So our final drift function is given by:

$$\begin{aligned}
K_a &= \sum_r \left[\phi_{a,r} - \frac{1}{2} e^{\bar{\mu}} (\phi_{a,r-\hat{\tau}} + \phi_{a,r+\hat{\tau}}) - \frac{i}{2} e^{\bar{\mu}} \epsilon_{ab} (\phi_{b,r-\hat{\tau}} + \phi_{b,r+\hat{\tau}}) \right. \\
&\quad + \frac{1}{2\bar{m}} \sum_{j=1}^d \left[2\phi_{a,r} - (\phi_{a,r+\hat{j}} + \phi_{c,r-\hat{j}}) - i \sum_{b=1}^2 \epsilon_{ab} (\phi_{b,r+\hat{j}} + \phi_{b,r-\hat{j}}) \right] \\
&\quad + \frac{\bar{m}\bar{\omega}_{\text{tr}}^2 \bar{r}_\perp^2}{4} \left(\phi_{a,r-\hat{\tau}} + \phi_{a,r+\hat{\tau}} + i \sum_{b=1}^2 \epsilon_{ab} (\phi_{b,r-\hat{\tau}} + \phi_{b,r+\hat{\tau}}) \right) \\
&\quad + \frac{\bar{\omega}_z}{2} \left(\sum_{b=1}^2 \epsilon_{ab} ((\bar{y} - \bar{x})(\phi_{b,r-\hat{\tau}} + \phi_{b,r+\hat{\tau}}) + \bar{x}(\phi_{b,r-\hat{y}-\hat{\tau}} + \phi_{b,r+\hat{y}+\hat{\tau}}) \right. \\
&\quad \left. - \bar{y}(\phi_{b,r-\hat{x}-\hat{\tau}} + \phi_{b,r+\hat{x}+\hat{\tau}})) + i((\bar{x} - \bar{y})(\phi_{a,r-\hat{\tau}} + \phi_{a,r+\hat{\tau}}) \right. \\
&\quad \left. - \bar{x}(\phi_{a,r-\hat{y}-\hat{\tau}} + \phi_{a,r+\hat{y}+\hat{\tau}}) + \bar{y}(\phi_{a,r-\hat{x}-\hat{\tau}} + \phi_{a,r+\hat{x}+\hat{\tau}})) \right) \\
&\quad + \frac{\bar{\lambda}}{4} \sum_{b=1}^2 [4\phi_{b,r}(\phi_{a,r+\hat{\tau}}\phi_{b,r+\hat{\tau}} + \phi_{a,r-\hat{\tau}}\phi_{b,r-\hat{\tau}}) - 2\phi_{a,r}(\phi_{b,r+\hat{\tau}}^2 + \phi_{b,r-\hat{\tau}}^2) \\
&\quad + 2i\epsilon_{ab}(\phi_{b,r}(\phi_{a,r+\hat{\tau}}^2 + \phi_{a,r-\hat{\tau}}^2) - \phi_{b,r}(\phi_{b,r+\hat{\tau}}^2 + \phi_{b,r-\hat{\tau}}^2) + 2\phi_{a,r}(\phi_{a,r-\hat{\tau}}\phi_{b,r-\hat{\tau}} + \phi_{a,r+\hat{\tau}}\phi_{b,r+\hat{\tau}}))] \quad \left. \right]
\end{aligned}$$

Which we can divide into real and imaginary contributions: $K_a = K_a^R + iK_a^I$:

$$\begin{aligned}
K_a^R &= \sum_r \left[\phi_{a,r} - \frac{1}{2} e^{\bar{\mu}} (\phi_{a,r-\hat{\tau}} + \phi_{a,r+\hat{\tau}}) + \frac{1}{2\bar{m}} \sum_{j=1}^d \left(2\phi_{a,r} - (\phi_{a,r+\hat{j}} + \phi_{c,r-\hat{j}}) \right) \right. \\
&\quad + \frac{\bar{m}\bar{\omega}_{\text{tr}}^2 \bar{r}_\perp^2}{4} (\phi_{a,r-\hat{\tau}} + \phi_{a,r+\hat{\tau}}) + \frac{\bar{\omega}_z}{2} \sum_{b=1}^2 \epsilon_{ab} \left((\bar{y} - \bar{x})(\phi_{b,r-\hat{\tau}} + \phi_{b,r+\hat{\tau}}) \right. \\
&\quad \left. \left. + \bar{x}(\phi_{b,r-\hat{y}-\hat{\tau}} + \phi_{b,r+\hat{y}+\hat{\tau}}) - \bar{y}(\phi_{b,r-\hat{x}-\hat{\tau}} + \phi_{b,r+\hat{x}+\hat{\tau}}) \right) \right. \\
&\quad \left. + \frac{\bar{\lambda}}{4} \sum_{b=1}^2 \left(4\phi_{b,r}(\phi_{a,r+\hat{\tau}}\phi_{b,r+\hat{\tau}} + \phi_{a,r-\hat{\tau}}\phi_{b,r-\hat{\tau}}) - 2\phi_{a,r}(\phi_{b,r+\hat{\tau}}^2 + \phi_{b,r-\hat{\tau}}^2) \right) \right] \\
K_a^I &= - \sum_r \left[\frac{1}{2} e^{\bar{\mu}} \epsilon_{ab} (\phi_{b,r-\hat{\tau}} + \phi_{b,r+\hat{\tau}}) + \frac{1}{2\bar{m}} \sum_{j=1}^d \left(\sum_{b=1}^2 \epsilon_{ab} (\phi_{b,r+\hat{j}} + \phi_{b,r-\hat{j}}) \right) \right. \\
&\quad - \frac{\bar{m}\bar{\omega}_{\text{tr}}^2 \bar{r}_\perp^2}{4} \left(\sum_{b=1}^2 \epsilon_{ab} (\phi_{b,r-\hat{\tau}} + \phi_{b,r+\hat{\tau}}) \right) - \frac{\bar{\omega}_z}{2} \left(((\bar{x} - \bar{y})(\phi_{a,r-\hat{\tau}} + \phi_{a,r+\hat{\tau}}) \right. \\
&\quad \left. \left. - \bar{x}(\phi_{a,r-\hat{y}-\hat{\tau}} + \phi_{a,r+\hat{y}+\hat{\tau}}) + \bar{y}(\phi_{a,r-\hat{x}-\hat{\tau}} + \phi_{a,r+\hat{x}+\hat{\tau}}) \right) \right) \\
&\quad - \frac{\bar{\lambda}}{2} \sum_{b=1}^2 \left(\epsilon_{ab} (\phi_{b,r}(\phi_{a,r+\hat{\tau}}^2 + \phi_{a,r-\hat{\tau}}^2) - \phi_{b,r}(\phi_{b,r+\hat{\tau}}^2 + \phi_{b,r-\hat{\tau}}^2) \right. \\
&\quad \left. \left. + 2\phi_{a,r}(\phi_{a,r-\hat{\tau}}\phi_{b,r-\hat{\tau}} + \phi_{a,r+\hat{\tau}}\phi_{b,r+\hat{\tau}}) \right) \right) \left. \right] \tag{A.25}
\end{aligned}$$

A.3.3 NOT UPDATED YET: Second Complexification of Drift Function

The next step is to complexify our real fields, a and b , such that $\phi_a = \phi_a^R + i\phi_a^I$. We do this for each part of the drift function, $K_{a,r} = \frac{\delta S_r}{\delta \phi_{a,r}}$.

First, the time and chemical potential term:

$$\begin{aligned}
2 \frac{\delta}{\delta \phi_{a,r}} S_{\mu,r} &= 2\phi_{a,r} - e^{d\tau\mu} (\phi_{a,r-\hat{\tau}} + \phi_{a,r+\hat{\tau}}) - ie^{d\tau\mu} \epsilon_{ab} (\phi_{b,r-\hat{\tau}} + \phi_{b,r+\hat{\tau}}) \\
&= 2(\phi_{a,r}^R + i\phi_{a,r}^I) - e^{d\tau\mu} (\phi_{a,r-\hat{\tau}}^R + i\phi_{a,r-\hat{\tau}}^I + \phi_{a,r+\hat{\tau}}^R + i\phi_{a,r+\hat{\tau}}^I) \\
&\quad - ie^{d\tau\mu} \epsilon_{ab} (\phi_{b,r-\hat{\tau}}^R + i\phi_{b,r-\hat{\tau}}^I + \phi_{b,r+\hat{\tau}}^R + i\phi_{b,r+\hat{\tau}}^I) \\
&= 2\phi_{a,r}^R - e^{d\tau\mu} (\phi_{a,r-\hat{\tau}}^R + \phi_{a,r+\hat{\tau}}^R) + e^{d\tau\mu} \epsilon_{ab} (\phi_{b,r-\hat{\tau}}^I - \phi_{b,r+\hat{\tau}}^I) \\
&\quad + i [2\phi_{a,r}^I - e^{d\tau\mu} (\phi_{a,r-\hat{\tau}}^I + \phi_{a,r+\hat{\tau}}^I) - e^{d\tau\mu} \epsilon_{ab} (\phi_{b,r-\hat{\tau}}^R - \phi_{b,r+\hat{\tau}}^R)]
\end{aligned}$$

So

$$\text{Re} \left[\frac{\delta}{\delta \phi_{a,r}} S_{\mu,r} \right] = \phi_{a,r}^R - \frac{e^{d\tau\mu}}{2} (\phi_{a,r-\hat{\tau}}^R + \phi_{a,r+\hat{\tau}}^R) + \frac{e^{d\tau\mu}}{2} \epsilon_{ab} (\phi_{b,r-\hat{\tau}}^I - \phi_{b,r+\hat{\tau}}^I) \tag{A.26}$$

$$\text{Im} \left[\frac{\delta}{\delta \phi_{a,r}} S_{\mu,r} \right] = \phi_{a,r}^I - \frac{e^{d\tau\mu}}{2} (\phi_{a,r-\hat{\tau}}^I + \phi_{a,r+\hat{\tau}}^I) - \frac{e^{d\tau\mu}}{2} \epsilon_{ab} (\phi_{b,r-\hat{\tau}}^R - \phi_{b,r+\hat{\tau}}^R) \tag{A.27}$$

Next, the spatial derivative part:

$$\begin{aligned}
-\frac{2m}{d\tau} \frac{\delta}{\delta\phi_{a,r}} S_{\nabla,r} &= \sum_{i=\pm 1}^d \phi_{a,r+\hat{i}} - 2d\phi_{a,r} \\
&= \sum_{i=\pm 1}^d \left(\phi_{a,r+\hat{i}}^R + i\phi_{a,r+\hat{i}}^I \right) - 2d\phi_{a,r}^R - 2id\phi_{a,r}^I \\
&= \sum_{i=\pm 1}^d \phi_{a,r+\hat{i}}^R - 2d\phi_{a,r}^R + i \left(\sum_{i=\pm 1}^d \phi_{a,r+\hat{i}}^I - 2d\phi_{a,r}^I \right)
\end{aligned}$$

So

$$\text{Re} \left[\frac{\delta}{\delta\phi_{a,r}} S_{\nabla,r} \right] = \frac{d\tau}{2m} \left(2d\phi_{a,r}^R - \sum_{i=\pm 1}^d \phi_{a,r+\hat{i}}^R \right) \quad (\text{A.28})$$

$$\text{Im} \left[\frac{\delta}{\delta\phi_{a,r}} S_{\nabla,r} \right] = \frac{d\tau}{2m} \left(2d\phi_{a,r}^I - \sum_{i=\pm 1}^d \phi_{a,r+\hat{i}}^I \right) \quad (\text{A.29})$$

Then the part of the action due to the external trapping potential:

$$\begin{aligned}
\frac{4}{d\tau m \omega_{\text{tr}}^2(r_{\perp}^2)} \frac{\delta}{\delta\phi_{a,r}} S_{\text{trap},r} &= \sum_{a=1}^2 \left((\phi_{a,r+\hat{\tau}} + \phi_{a,r-\hat{\tau}}) + i \sum_{b=1}^2 \epsilon_{ab} (\phi_{b,r+\hat{\tau}} + \phi_{b,r-\hat{\tau}}) \right) \\
&= \sum_{a=1}^2 \left((\phi_{a,r+\hat{\tau}}^R + \phi_{a,r-\hat{\tau}}^R) - \sum_{b=1}^2 \epsilon_{ab} (\phi_{b,r+\hat{\tau}}^I + \phi_{b,r-\hat{\tau}}^I) \right) \\
&\quad + i \sum_{a=1}^2 \left((\phi_{a,r+\hat{\tau}}^I + \phi_{a,r-\hat{\tau}}^I) + \sum_{b=1}^2 \epsilon_{ab} (\phi_{b,r+\hat{\tau}}^R + \phi_{b,r-\hat{\tau}}^R) \right) \quad (\text{A.30})
\end{aligned}$$

So

$$\text{Re} \left[\frac{\delta}{\delta\phi_{a,r}} S_{\text{trap},r} \right] = \frac{d\tau \omega_{\text{tr}}^2(r_{\perp}^2)}{4} \sum_{a=1}^2 \left((\phi_{a,r+\hat{\tau}}^R + \phi_{a,r-\hat{\tau}}^R) - \sum_{b=1}^2 \epsilon_{ab} (\phi_{b,r+\hat{\tau}}^I + \phi_{b,r-\hat{\tau}}^I) \right) \quad (\text{A.31})$$

$$\text{Im} \left[\frac{\delta}{\delta\phi_{a,r}} S_{\text{trap},r} \right] = \frac{d\tau \omega_{\text{tr}}^2(r_{\perp}^2)}{4} \sum_{a=1}^2 \left((\phi_{a,r+\hat{\tau}}^I + \phi_{a,r-\hat{\tau}}^I) + \sum_{b=1}^2 \epsilon_{ab} (\phi_{b,r+\hat{\tau}}^R + \phi_{b,r-\hat{\tau}}^R) \right) \quad (\text{A.32})$$

where $r_{\perp}^2 = x^2 + y^2$. Next, the rotational piece:

$$\begin{aligned}
\frac{2}{d\tau \omega_z} \frac{\delta}{\delta\phi_{a,r}} S_{\omega,r} &= \epsilon_{ab} [x(\phi_{b,r-\hat{y}} + \phi_{b,r+\hat{y}}) - y(\phi_{b,r-\hat{x}} + \phi_{b,r+\hat{x}})] \\
&\quad + i[2(x-y)\phi_{a,r} - x(\phi_{a,r-\hat{y}} + \phi_{a,r+\hat{y}}) + y(\phi_{a,r-\hat{x}} + \phi_{a,r+\hat{x}})] \\
&= \epsilon_{ab} [x(\phi_{b,r-\hat{y}}^R + i\phi_{b,r-\hat{y}}^I + \phi_{b,r+\hat{y}}^R + i\phi_{b,r+\hat{y}}^I) - y(\phi_{b,r-\hat{x}}^R + i\phi_{b,r-\hat{x}}^I + \phi_{b,r+\hat{x}}^R + i\phi_{b,r+\hat{x}}^I)] \\
&\quad + i[2(x-y)\phi_{a,r}^R + 2i(x-y)\phi_{a,r}^I - x(\phi_{a,r-\hat{y}}^R + i\phi_{a,r-\hat{y}}^I + \phi_{a,r+\hat{y}}^R + i\phi_{a,r+\hat{y}}^I)] \\
&\quad + i[y(\phi_{a,r-\hat{x}}^R + i\phi_{a,r-\hat{x}}^I + \phi_{a,r+\hat{x}}^R + i\phi_{a,r+\hat{x}}^I)] \\
&= -2(x-y)\phi_{a,r}^I + x(\phi_{a,r-\hat{y}}^I + \phi_{a,r+\hat{y}}^I) - y(\phi_{a,r-\hat{x}}^I + \phi_{a,r+\hat{x}}^I) \\
&\quad + \epsilon_{ab} [x(\phi_{b,r-\hat{y}}^R + \phi_{b,r+\hat{y}}^R) - y(\phi_{b,r-\hat{x}}^R + \phi_{b,r+\hat{x}}^R)] \\
&\quad + i[2(x-y)\phi_{a,r}^R - x(\phi_{a,r-\hat{y}}^R + \phi_{a,r+\hat{y}}^R) + y(\phi_{a,r-\hat{x}}^R + \phi_{a,r+\hat{x}}^R)] \\
&\quad + i\epsilon_{ab} [x(\phi_{b,r-\hat{y}}^I + \phi_{b,r+\hat{y}}^I) - y(\phi_{b,r-\hat{x}}^I + \phi_{b,r+\hat{x}}^I)] \quad (\text{A.33})
\end{aligned}$$

So

$$\begin{aligned}
\text{Re} \left[\frac{\delta}{\delta \phi_{a,r}} S_{\omega_z, r} \right] &= \frac{d\tau \omega_z}{2} [x (\phi_{a,r-\hat{y}}^I + \phi_{a,r+\hat{y}}^I) - y (\phi_{a,r-\hat{x}}^I + \phi_{a,r+\hat{x}}^I) - 2(x-y)\phi_{a,r}^I] \\
&\quad + \frac{d\tau \omega_z}{2} \epsilon_{ab} [x (\phi_{b,r-\hat{y}}^R + \phi_{b,r+\hat{y}}^R) - y (\phi_{b,r-\hat{x}}^R + \phi_{b,r+\hat{x}}^R)] \\
\text{Im} \left[\frac{\delta}{\delta \phi_{a,r}} S_{\omega_z, r} \right] &= \frac{d\tau \omega_z}{2} [2(x-y)\phi_{a,r}^R - x (\phi_{a,r-\hat{y}}^R + \phi_{a,r+\hat{y}}^R) + y (\phi_{a,r-\hat{x}}^R + \phi_{a,r+\hat{x}}^R)] \quad (\text{A.34}) \\
&\quad + \frac{\omega_z}{2} \epsilon_{ab} [x (\phi_{b,r-\hat{y}}^I + \phi_{b,r+\hat{y}}^I) - y (\phi_{b,r-\hat{x}}^I + \phi_{b,r+\hat{x}}^I)]
\end{aligned}$$

And finally, the interaction term in the action:

$$\begin{aligned}
\frac{1}{d\tau \lambda} \frac{\delta}{\delta \phi_{a,r}} S_{\text{int}, r} &= \phi_{a,r} \sum_{b=1}^2 \phi_{b,r}^2 \\
&= (\phi_{a,r}^R + i\phi_{a,r}^I) \sum_{b=1}^2 (\phi_{b,r}^R + i\phi_{b,r}^I)^2 \\
&= \phi_{a,r}^R \sum_{b=1}^2 ((\phi_{b,r}^R)^2 + 2i\phi_{b,r}^R \phi_{b,r}^I - (\phi_{b,r}^I)^2) + i\phi_{a,r}^I \sum_{b=1}^2 ((\phi_{b,r}^R)^2 + 2i\phi_{b,r}^R \phi_{b,r}^I - (\phi_{b,r}^I)^2) \\
&= \sum_{b=1}^2 [\phi_{a,r}^R (\phi_{b,r}^R)^2 + 2i\phi_{a,r}^R \phi_{b,r}^R \phi_{b,r}^I - \phi_{a,r}^R (\phi_{b,r}^I)^2 + i\phi_{a,r}^I (\phi_{b,r}^R)^2 - 2\phi_{a,r}^I \phi_{b,r}^R \phi_{b,r}^I - i\phi_{a,r}^I (\phi_{b,r}^I)^2] \\
&= \sum_{b=1}^2 [\phi_{a,r}^R (\phi_{b,r}^R)^2 - \phi_{a,r}^R (\phi_{b,r}^I)^2 - 2\phi_{a,r}^I \phi_{b,r}^R \phi_{b,r}^I] + i \sum_{b=1}^2 [2\phi_{a,r}^R \phi_{b,r}^R \phi_{b,r}^I + \phi_{a,r}^I (\phi_{b,r}^R)^2 - \phi_{a,r}^I (\phi_{b,r}^I)^2]
\end{aligned}$$

So

$$\text{Re} \left[\frac{\delta}{\delta \phi_{a,r}} S_{\text{int}, r} \right] = d\tau \lambda \sum_{b=1}^2 [\phi_{a,r}^R (\phi_{b,r}^R)^2 - \phi_{a,r}^R (\phi_{b,r}^I)^2 - 2\phi_{a,r}^I \phi_{b,r}^R \phi_{b,r}^I] \quad (\text{A.35})$$

$$\text{Im} \left[\frac{\delta}{\delta \phi_{a,r}} S_{\text{int}, r} \right] = d\tau \lambda \sum_{b=1}^2 [\phi_{a,r}^I (\phi_{b,r}^R)^2 + 2\phi_{a,r}^R \phi_{b,r}^R \phi_{b,r}^I - \phi_{a,r}^I (\phi_{b,r}^I)^2] \quad (\text{A.36})$$

A.4 Lattice Observables

The observables we are interested in calculating are:

- particle density (local and average density)
- angular momentum
- field modulus squared
- harmonic trapping potential energy
- interaction potential energy
- kinetic energy

- total energy
- circulation

Most of our observables can be determined by taking appropriate derivatives of $\ln \mathcal{Z}$, with the exception of the field modulus squared and the circulation. The general form for this argument is shown below.

We have a partition function, \mathcal{Z} ,

$$\mathcal{Z} = \int \mathcal{D}\phi e^{-S[\phi]} \quad (\text{A.37})$$

Observables are calculated via a path integral as well, where the integrand includes the observable as a function of the fields, weighted by e^{-S} :

$$\langle \mathcal{O} \rangle = \frac{1}{\mathcal{Z}} \int \mathcal{D}\phi \mathcal{O}[\phi] e^{-S[\phi]} \quad (\text{A.38})$$

If we take a derivative of the log of \mathcal{Z} with respect to some parameter α , we get something that looks very similar to this expression:

$$\frac{\partial \ln \mathcal{Z}}{\partial \alpha} = \frac{1}{\mathcal{Z}} \frac{\partial \mathcal{Z}}{\partial \alpha} = \frac{1}{\mathcal{Z}} \int \mathcal{D}\phi \left(-\frac{\partial S[\phi, \alpha]}{\partial \alpha} \right) e^{-S[\phi, \alpha]} \quad (\text{A.39})$$

which suggests that we can compute observables by taking derivatives of the action

$$\hat{\mathcal{O}}_\alpha = -\frac{\partial}{\partial \alpha} S[\phi, \alpha] \quad (\text{A.40})$$

In our statistical simulation, we seek to compute average values of these observables, weighted by e^{-S} . The complex Langevin simulation ensures that our samples are distributed according to the proper weight, so we are able to perform a simple average of the observables after the simulation has thermalized.

[NOTE: where does the beta come in? Or do we just need to take derivatives wrt our lattice parameters (e.g. $\bar{\mu}$ instead of μ)?]

A.4.1 Density

To calculate the density, first we need to determine the total number of particles in the system. We can do this by taking a derivative of the lattice action with respect to the chemical potential. Since the only part of the lattice action that depends on $\bar{\mu}$ is S_μ , we can ignore the rest of the action:

$$\begin{aligned} \hat{N}[\phi_i] &= \frac{\partial}{\partial \bar{\mu}} S_{lat} = \frac{\partial}{\partial \bar{\mu}} S_\mu = \frac{\partial}{\partial \bar{\mu}} \sum_{\vec{x}, \tau} a^d (\phi_r^* \phi_r - e^{\bar{\mu}} \phi_r^* \phi_{r-\hat{\tau}}) \\ &= \sum_{\vec{x}, \tau} a^d (e^{\bar{\mu}} \phi_r^* \phi_{r-\hat{\tau}}). \end{aligned} \quad (\text{A.41})$$

This can be written in terms of S_μ :

$$\hat{N}[\phi_i] = \sum_{\vec{x}, \tau} a^d \phi_r^* \phi_r - S_\mu \quad (\text{A.42})$$

To determine the density, we simply normalize the particle number by the spatial lattice volume:

$$\hat{n}[\phi_i] = \frac{1}{(aN_x)^d} \hat{N}[\phi_i] \quad (\text{A.43})$$

Complexification

When we apply the complexification to the real fields, $\phi_{a/b} \rightarrow \phi_{a/b}^R + i\phi_{a/b}^I$, we get:

$$\begin{aligned}
\hat{n} &= \frac{1}{2N_x^d} e^{\bar{\mu}} \sum_{\vec{x}, \tau} \sum_{a,b=1}^2 (\delta_{ab} \phi_{a,r} \phi_{b,r-\hat{\tau}} + i\epsilon_{ab} \phi_{a,r} \phi_{b,r-\hat{\tau}}) \\
&= \frac{1}{2N_x^d} e^{\bar{\mu}} \sum_{\vec{x}, \tau} \sum_{a,b=1}^2 [\delta_{ab} (\phi_{a,r}^R \phi_{r,b-\hat{\tau}}^R - \phi_{a,r}^I \phi_{r,b-\hat{\tau}}^I) - \epsilon_{ab} (\phi_{a,r}^R \phi_{r,b-\hat{\tau}}^I + \phi_{a,r}^I \phi_{r,b-\hat{\tau}}^R)] \\
&\quad \frac{i}{2N_x^d} e^{\bar{\mu}} \sum_{\vec{x}, \tau} \sum_{a,b=1}^2 [\delta_{ab} (\phi_{a,r}^R \phi_{r,b-\hat{\tau}}^I + \phi_{a,r}^I \phi_{r,b-\hat{\tau}}^R) + \epsilon_{ab} (\phi_{a,r}^R \phi_{r,b-\hat{\tau}}^R - \phi_{a,r}^I \phi_{r,b-\hat{\tau}}^I)] \quad (\text{A.44})
\end{aligned}$$

This was done in Mathematica. **[NOTE: outstanding questions – where did this extra overall minus sign come from, and is the $1/Nx^d$ the same one we use when taking the average?]**

A.4.2 Local Density

The local density is simply the density function without the sum over the lattice. Since we are concerned with spatial density, we can either average our results over the extent of the time lattice

$$\hat{n}_r[\phi_i, \vec{x}] = \frac{1}{N_\tau (aN_x)^d} \sum_{\tau} a^d (e^{\bar{\mu}} \phi_r^* \phi_{r-\hat{\tau}}) \quad (\text{A.45})$$

or take the density profile of a single time slice:

$$\hat{n}_r[\phi_i, \vec{x}, \tau] = \frac{1}{(aN_x)^d} a^d (e^{\bar{\mu}} \phi_r^* \phi_{r-\hat{\tau}}) \quad (\text{A.46})$$

Averaging over the extent of the time lattice should produce better results (i.e. we will have a mean and a standard error, which gives us a statistical value to evaluate), so we will do this.

Complexification

The difference between this observable and the density is simply that we evaluate the local density at each site and then do not average over the entire spatial lattice. The complexified observable value is therefore the same, after removing the sum over \vec{x} .

A.4.3 Field Modulus Squared

The field modulus squared is simply a measure of the magnitude of the complex field, ϕ . This can be written straightforwardly as

$$\phi^* \phi = \sum_{\vec{x}, \tau} a^d d\tau \phi_{r,\tau}^* \phi_{r,\tau} \quad (\text{A.47})$$

While this is not an incredibly useful quantity to calculate, it's very simple and can be used in some early testing to ensure stability of the method and check against other results.

Complexification

When we apply the complexification to the real fields, $\phi_{a/b} \rightarrow \phi_{a/b}^R + i\phi_{a/b}^I$, we get:

$$\begin{aligned}\phi^* \phi &= \frac{1}{2} \sum_{\vec{x}, \tau} a^d \sum_{a=1}^2 d\tau (\phi_{a,r} \phi_{a,r}) \\ &= \frac{1}{2} \sum_{\vec{x}, \tau} a^d \sum_{a=1}^2 d\tau [((\phi_{a,r}^R)^2 - (\phi_{a,r}^I)^2) + i\phi_{a,r}^R \phi_{a,r}^I]\end{aligned}\tag{A.48}$$

This was done in Mathematica.

[NOTE: outstanding questions – this extra factor of $d\tau$ should be divided out – where does that come from? Is it just part of the observable? You’ll want to prove this before submitting the paper – look at the analytical solutions for the field modulus]

A.4.4 Angular Momentum

We can compute the angular momentum by taking a derivative of the lattice action with respect to the rotation frequency. Since the only part of the lattice action that depends on $\bar{\omega}_z$ is S_ω , we can ignore the rest of the action:

$$\begin{aligned}\hat{L}_z[\phi_i] &= -\frac{\partial}{\partial \bar{\omega}_z} S_{lat} = \frac{\partial}{\partial \bar{\omega}_z} S_\omega \\ &= \frac{\partial}{\partial \bar{\omega}_z} \sum_{\vec{x}, \tau} a^d (i\bar{\omega}_z (\bar{x}\phi_r^* \phi_{r-\hat{\tau}} - \bar{x}\phi_r^* \phi_{r-\hat{y}-\hat{\tau}} - \bar{y}\phi_r^* \phi_{r-\hat{\tau}} + \bar{y}\phi_r^* \phi_{r-\hat{x}-\hat{\tau}})) \\ &= \sum_{\vec{x}, \tau} a^d (i(\bar{x}\phi_r^* \phi_{r-\hat{\tau}} - \bar{x}\phi_r^* \phi_{r-\hat{y}-\hat{\tau}} - \bar{y}\phi_r^* \phi_{r-\hat{\tau}} + \bar{y}\phi_r^* \phi_{r-\hat{x}-\hat{\tau}}))\end{aligned}\tag{A.49}$$

This can be written in terms of S_ω :

$$\hat{L}_z[\phi_i] = \frac{1}{\bar{\omega}_z} S_\omega\tag{A.50}$$

[NOTE: Check the sign here – you may have lost a minus sign]

Complexification

When we apply the complexification to the real fields, $\phi_{a/b} \rightarrow \phi_{a/b}^R + i\phi_{a/b}^I$, we get:

$$\begin{aligned}
\hat{L}_z[\phi_i] &= \frac{1}{2} \sum_{a=1}^2 \left[\sum_{b=1}^2 \epsilon_{ab} ((\bar{y} - \bar{x})\phi_{a,r}\phi_{b,r-\hat{\tau}} + \bar{x}\phi_{a,r}\phi_{b,r-\hat{y}-\hat{\tau}} - \bar{y}\phi_{a,r}\phi_{b,r-\hat{x}-\hat{\tau}}) \right] \\
&\quad + i \frac{1}{2} \sum_{a=1}^2 [(\bar{x} - \bar{y})\phi_{a,r}\phi_{a,r-\hat{\tau}} - \bar{x}\phi_{a,r}\phi_{a,r-\hat{y}-\hat{\tau}} + \bar{y}\phi_{a,r}\phi_{a,r-\hat{x}-\hat{\tau}}] \\
&= \frac{1}{2} \sum_{a=1}^2 [(y-x)\phi_{a,r}^R\phi_{a,r-\hat{\tau}}^I + (y-x)\phi_{a,r}^I\phi_{a,r-\hat{\tau}}^R \\
&\quad + x\phi_{a,r}^R\phi_{a,r-\hat{\tau}-\hat{y}}^I + x\phi_{a,r}^I\phi_{a,r-\hat{\tau}-\hat{y}}^R - y\phi_{a,r}^R\phi_{a,r-\hat{\tau}-\hat{x}}^I - y\phi_{a,r}^I\phi_{a,r-\hat{\tau}-\hat{x}}^R \\
&\quad + \epsilon_{ab} \sum_{b=1}^2 ((x-y)\phi_{a,r}^I\phi_{b,r-\hat{\tau}}^I + (y-x)\phi_{a,r}^R\phi_{b,r-\hat{\tau}}^R \\
&\quad + x\phi_{a,r}^R\phi_{b,r-\hat{\tau}-\hat{y}}^R - x\phi_{a,r}^I\phi_{b,r-\hat{\tau}-\hat{y}}^I + y\phi_{a,r}^I\phi_{b,r-\hat{\tau}-\hat{x}}^I - y\phi_{a,r}^R\phi_{b,r-\hat{\tau}-\hat{x}}^R)] \\
&\quad + \frac{i}{2} \sum_{a=1}^2 [(x-y)\phi_{a,r}^R\phi_{a,r-\hat{\tau}}^R + (y-x)\phi_{a,r}^I\phi_{a,r-\hat{\tau}}^I - x\phi_{a,r}^R\phi_{a,r-\hat{\tau}-\hat{y}}^R \\
&\quad + x\phi_{a,r}^I\phi_{a,r-\hat{\tau}-\hat{y}}^I + y\phi_{a,r}^R\phi_{a,r-\hat{\tau}-\hat{x}}^R - y\phi_{a,r}^I\phi_{a,r-\hat{\tau}-\hat{x}}^I \\
&\quad + \epsilon_{ab} \sum_{b=1}^2 ((y-x)\phi_{a,r}^R\phi_{b,r-\hat{\tau}}^I + (y-x)\phi_{a,r}^I\phi_{b,r-\hat{\tau}}^R + x\phi_{a,r}^R\phi_{b,r-\hat{\tau}-\hat{y}}^I \\
&\quad + x\phi_{a,r}^I\phi_{b,r-\hat{\tau}-\hat{y}}^R - y\phi_{a,r}^R\phi_{b,r-\hat{\tau}-\hat{x}}^I - y\phi_{a,r}^I\phi_{b,r-\hat{\tau}-\hat{x}}^R)] \tag{A.51}
\end{aligned}$$

[NOTE: You lost your \bar{x} and \bar{y} along the way, so check for that. It should be correct except for not having the bar over it, but better to confirm...]

A.4.5 Harmonic Trapping Potential Energy

As is likely obvious by now, the way to calculate the potential energy due to the harmonic trap is by taking a derivative with respect to $\bar{\omega}_{\text{tr}}$. The only part of the action that depends on $\bar{\omega}_{\text{tr}}$ is S_{tr} :

$$\begin{aligned}
\hat{V}_{\text{tr}}[\phi_i] &= -\frac{\partial}{\partial \bar{\omega}_{\text{tr}}} S_{\text{lat}} = \frac{\partial}{\partial \bar{\omega}_{\text{tr}}} S_{\text{tr}} \\
&= \frac{\partial}{\partial \bar{\omega}_{\text{tr}}} \sum_{\vec{x}, \tau} a^d \left(\frac{\bar{m}}{2} \bar{\omega}_{\text{tr}}^2 \bar{r}_{\perp}^2 \phi_r^* \phi_{r-\hat{\tau}} \right) = \sum_{\vec{x}, \tau} a^d \left(\frac{\bar{m}}{2} (2\bar{\omega}_{\text{tr}}) \bar{r}_{\perp}^2 \phi_r^* \phi_{r-\hat{\tau}} \right) \\
&= \sum_{\vec{x}, \tau} a^d (\bar{m} \bar{\omega}_{\text{tr}} \bar{r}_{\perp}^2 \phi_r^* \phi_{r-\hat{\tau}}) \tag{A.52}
\end{aligned}$$

In terms of S_{tr} , this is

$$V_{\text{tr}} = \frac{2}{\bar{\omega}_{\text{tr}}} S_{\text{tr}} \tag{A.53}$$

[NOTE: Check the sign here as well]

Complexification

When we apply the complexification to the real fields, $\phi_{a/b} \rightarrow \phi_{a/b}^R + i\phi_{a/b}^I$, we get:

$$\begin{aligned}
V_{\text{tr}} &= \sum_{\vec{x}, \tau} a^d \frac{\bar{m}}{2} \bar{\omega}_{\text{tr}} \bar{r}_{\perp}^2 \sum_{a=1}^2 \left[\phi_{a,r} \phi_{a,r-\hat{\tau}} + i \sum_{b=1}^2 \epsilon_{ab} \phi_{a,r} \phi_{b,r-\hat{\tau}} \right] \\
&= \frac{\bar{m}}{2} \bar{\omega}_{\text{tr}} \bar{r}_{\perp}^2 \sum_{\vec{x}, \tau} a^d \sum_{a=1}^2 \left[\phi_{a,r}^R \phi_{a,r-\hat{\tau}}^R - \phi_{a,r}^I \phi_{a,r-\hat{\tau}}^I - \epsilon_{ab} (\phi_{a,r}^R \phi_{b,r-\hat{\tau}}^I + \phi_{a,r}^I \phi_{b,r-\hat{\tau}}^R) \right] \\
&\quad + i \frac{\bar{m}}{2} \bar{\omega}_{\text{tr}} \bar{r}_{\perp}^2 \sum_{\vec{x}, \tau} a^d \sum_{a=1}^2 \left[\phi_{a,r}^R \phi_{a,r-\hat{\tau}}^I + \phi_{a,r}^I \phi_{a,r-\hat{\tau}}^R + \epsilon_{ab} (\phi_{a,r}^R \phi_{b,r-\hat{\tau}}^R - \phi_{a,r}^I \phi_{b,r-\hat{\tau}}^I) \right] \quad (\text{A.54})
\end{aligned}$$

A.4.6 Interaction Potential Energy

The interaction also generates a potential energy, and we can calculate that by taking a derivative as well. The interaction parameter, $\bar{\lambda}$, is only present in the interaction term, S_{int} :

$$\begin{aligned}
\hat{V}_{\text{int}}[\phi_i] &= -\frac{\partial}{\partial \bar{\lambda}} S_{\text{int}} = -\frac{\partial}{\partial \bar{\lambda}} S_{\text{int}} \\
&= -\frac{\partial}{\partial \bar{\lambda}} \sum_{\vec{x}, \tau} a^d (\bar{\lambda} (\phi_r^* \phi_{r-\hat{\tau}})^2) = -\sum_{\vec{x}, \tau} a^d (\phi_r^* \phi_{r-\hat{\tau}})^2. \quad (\text{A.55})
\end{aligned}$$

In terms of $S_{\bar{\lambda}}$, this is:

$$\hat{V}_{\text{int}} = \frac{1}{\bar{\lambda}} S_{\bar{\lambda}} \quad (\text{A.56})$$

Complexification

When we apply the complexification to the real fields, $\phi_{a/b} \rightarrow \phi_{a/b}^R + i\phi_{a/b}^I$, we get:

$$\begin{aligned}
\hat{V}_{\text{int}} &= \frac{1}{4} \sum_{\vec{x}, \tau} a^d \sum_{a,b=1}^2 [2\phi_{a,r}\phi_{a,r-\hat{\tau}}\phi_{b,r}\phi_{b,r-\hat{\tau}} - \phi_{a,r}^2\phi_{b,r-\hat{\tau}}^2] \\
&\quad + i\frac{\bar{\lambda}}{2} \sum_{\vec{x}, \tau} a^d \sum_{a,b=1}^2 [\epsilon_{ab} (\phi_{a,r}^2\phi_{a,r-\hat{\tau}}\phi_{b,r-\hat{\tau}} - \phi_{a,r}\phi_{b,r}\phi_{a,r-\hat{\tau}}^2)] \\
&= \frac{1}{4} \sum_{\vec{x}, \tau} a^d \sum_{a,b=1}^2 [4\phi_{a,r}^R\phi_{a,r}^I\phi_{b,r-\hat{\tau}}^R\phi_{b,r-\hat{\tau}}^I \\
&\quad + \phi_{a,r}^R\phi_{a,r}^R\phi_{b,r-\hat{\tau}}^I\phi_{b,r-\hat{\tau}}^I + \phi_{a,r}^I\phi_{a,r}^I\phi_{b,r-\hat{\tau}}^R\phi_{b,r-\hat{\tau}}^R \\
&\quad - \phi_{a,r}^R\phi_{a,r}^R\phi_{b,r-\hat{\tau}}^R\phi_{b,r-\hat{\tau}}^R - \phi_{a,r}^I\phi_{a,r}^I\phi_{b,r-\hat{\tau}}^I\phi_{b,r-\hat{\tau}}^I \\
&\quad + 2\phi_{a,r}^R\phi_{a,r-\hat{\tau}}^R\phi_{b,r}^R\phi_{b,r-\hat{\tau}}^R + 2\phi_{a,r}^I\phi_{a,r-\hat{\tau}}^I\phi_{b,r}^I\phi_{b,r-\hat{\tau}}^I \\
&\quad - 2\phi_{a,r}^R\phi_{a,r-\hat{\tau}}^R\phi_{b,r}^I\phi_{b,r-\hat{\tau}}^I - 2\phi_{a,r}^I\phi_{a,r-\hat{\tau}}^I\phi_{b,r}^R\phi_{b,r-\hat{\tau}}^R \\
&\quad - 2\phi_{a,r}^R\phi_{a,r-\hat{\tau}}^I\phi_{b,r}^R\phi_{b,r-\hat{\tau}}^I - 2\phi_{a,r}^I\phi_{a,r-\hat{\tau}}^R\phi_{b,r}^I\phi_{b,r-\hat{\tau}}^R \\
&\quad - 2\phi_{a,r}^R\phi_{a,r-\hat{\tau}}^I\phi_{b,r}^I\phi_{b,r-\hat{\tau}}^R - 2\phi_{a,r}^I\phi_{a,r-\hat{\tau}}^R\phi_{b,r}^R\phi_{b,r-\hat{\tau}}^I \\
&\quad + \epsilon_{ab}(\phi_{a,r}^R\phi_{a,r-\hat{\tau}}^R\phi_{b,r}^R\phi_{b,r-\hat{\tau}}^I + \phi_{a,r}^I\phi_{a,r-\hat{\tau}}^R\phi_{b,r}^R\phi_{b,r-\hat{\tau}}^R \\
&\quad - \phi_{a,r}^R\phi_{a,r-\hat{\tau}}^I\phi_{b,r}^I\phi_{b,r-\hat{\tau}}^I - \phi_{a,r}^I\phi_{a,r-\hat{\tau}}^I\phi_{b,r}^I\phi_{b,r-\hat{\tau}}^R \\
&\quad + \phi_{a,r}^I\phi_{a,r}^I\phi_{b,r-\hat{\tau}}^I\phi_{b,r-\hat{\tau}}^R + \phi_{a,r}^I\phi_{a,r}^I\phi_{b,r-\hat{\tau}}^R\phi_{b,r-\hat{\tau}}^I \\
&\quad - \phi_{a,r}^R\phi_{a,r}^R\phi_{b,r-\hat{\tau}}^I\phi_{b,r-\hat{\tau}}^R - \phi_{a,r}^R\phi_{a,r}^R\phi_{b,r-\hat{\tau}}^R\phi_{b,r-\hat{\tau}}^I \\
&\quad + 2\phi_{a,r}^R\phi_{b,r}^R\phi_{a,r-\hat{\tau}}^R\phi_{a,r-\hat{\tau}}^I + 2\phi_{a,r}^R\phi_{a,r}^I\phi_{b,r-\hat{\tau}}^I\phi_{b,r-\hat{\tau}}^I \\
&\quad - 2\phi_{a,r}^R\phi_{a,r}^I\phi_{b,r-\hat{\tau}}^R\phi_{b,r-\hat{\tau}}^R - 2\phi_{a,r}^I\phi_{b,r}^I\phi_{a,r-\hat{\tau}}^R\phi_{a,r-\hat{\tau}}^I)] \\
&\quad + i\frac{1}{4} \sum_{\vec{x}, \tau} a^d \sum_{a,b=1}^2 [\\
&\quad 2\phi_{a,r}^I\phi_{a,r}^I\phi_{b,r-\hat{\tau}}^R\phi_{b,r-\hat{\tau}}^I - 2\phi_{a,r}^R\phi_{a,r}^R\phi_{b,r-\hat{\tau}}^R\phi_{b,r-\hat{\tau}}^I \\
&\quad + 2\phi_{a,r}^R\phi_{a,r}^I\phi_{b,r-\hat{\tau}}^I\phi_{b,r-\hat{\tau}}^I - 2\phi_{a,r}^R\phi_{a,r}^I\phi_{b,r-\hat{\tau}}^R\phi_{b,r-\hat{\tau}}^R \\
&\quad + 2\phi_{a,r}^R\phi_{b,r}^R\phi_{a,r-\hat{\tau}}^I\phi_{b,r-\hat{\tau}}^R - 2\phi_{a,r}^I\phi_{b,r}^I\phi_{a,r-\hat{\tau}}^I\phi_{b,r-\hat{\tau}}^R \\
&\quad + 2\phi_{a,r}^R\phi_{b,r}^R\phi_{a,r-\hat{\tau}}^R\phi_{b,r-\hat{\tau}}^I - 2\phi_{a,r}^I\phi_{b,r}^I\phi_{a,r-\hat{\tau}}^R\phi_{b,r-\hat{\tau}}^I \\
&\quad + 2\phi_{a,r}^R\phi_{b,r}^I\phi_{a,r-\hat{\tau}}^R\phi_{b,r-\hat{\tau}}^R - 2\phi_{a,r}^R\phi_{b,r}^I\phi_{a,r-\hat{\tau}}^I\phi_{b,r-\hat{\tau}}^I \\
&\quad + 2\phi_{a,r}^I\phi_{b,r}^R\phi_{a,r-\hat{\tau}}^I\phi_{b,r-\hat{\tau}}^R - 2\phi_{a,r}^I\phi_{b,r}^R\phi_{a,r-\hat{\tau}}^R\phi_{b,r-\hat{\tau}}^I \\
&\quad + \epsilon_{ab}(\phi_{a,r}^R\phi_{a,r}^R\phi_{b,r-\hat{\tau}}^R\phi_{b,r-\hat{\tau}}^I - \phi_{a,r}^R\phi_{a,r}^R\phi_{b,r-\hat{\tau}}^I\phi_{b,r-\hat{\tau}}^I \\
&\quad + \phi_{a,r}^I\phi_{a,r}^I\phi_{b,r-\hat{\tau}}^I\phi_{b,r-\hat{\tau}}^I - \phi_{a,r}^I\phi_{a,r}^I\phi_{b,r-\hat{\tau}}^R\phi_{b,r-\hat{\tau}}^R \\
&\quad + \phi_{a,r}^I\phi_{b,r}^I\phi_{a,r-\hat{\tau}}^R\phi_{a,r-\hat{\tau}}^R - \phi_{a,r}^R\phi_{b,r}^R\phi_{a,r-\hat{\tau}}^I\phi_{a,r-\hat{\tau}}^I \\
&\quad + \phi_{a,r}^R\phi_{b,r}^R\phi_{a,r-\hat{\tau}}^I\phi_{a,r-\hat{\tau}}^I - \phi_{a,r}^I\phi_{b,r}^I\phi_{a,r-\hat{\tau}}^R\phi_{a,r-\hat{\tau}}^R \\
&\quad + 2\phi_{a,r}^R\phi_{b,r}^I\phi_{a,r-\hat{\tau}}^R\phi_{a,r-\hat{\tau}}^I + 2\phi_{a,r}^I\phi_{b,r}^R\phi_{a,r-\hat{\tau}}^R\phi_{a,r-\hat{\tau}}^I \\
&\quad - 2\phi_{a,r}^R\phi_{a,r}^I\phi_{b,r-\hat{\tau}}^R\phi_{b,r-\hat{\tau}}^I - 2\phi_{a,r}^R\phi_{a,r}^I\phi_{b,r-\hat{\tau}}^I\phi_{b,r-\hat{\tau}}^R)] \tag{A.57}
\end{aligned}$$

A.4.7 Kinetic Energy

Of course, in addition to the potential energies, our system has a kinetic energy, which we can calculate. The kinetic energy is actually one of the terms in the action, and we don't need to perform any derivatives to calculate it:

$$\hat{T} = S_{\nabla} = \sum_{\vec{x}, \tau} a^d \left(\frac{1}{2\bar{m}} \sum_{j=1}^d (2\phi_r^* \phi_r - \phi_r^* \phi_{r-\hat{j}} - \phi_r^* \phi_{r+\hat{j}}) \right) \quad (\text{A.58})$$

Complexification

$$\begin{aligned} \hat{T} &= \frac{1}{4\bar{m}} \sum_{\vec{x}, \tau} a^d \sum_{j=1}^d \sum_{a=1}^2 \left[2\phi_{a,r}^2 - (\phi_a \phi_{a,r-\hat{j}} + \phi_a \phi_{a,r+\hat{j}}) \right. \\ &\quad \left. - i \sum_{b=1}^2 \epsilon_{ab} (\phi_{a,r} \phi_{b,r-\hat{j}} + \phi_{a,r} \phi_{b,r+\hat{j}}) \right] \\ &= \frac{1}{4\bar{m}} \sum_{\vec{x}, \tau} a^d \sum_{j=1}^d \sum_{a=1}^2 \left[2\phi_{a,r}^R \phi_{a,r}^R - 2\phi_{a,r}^I \phi_{a,r}^I \right. \\ &\quad + \phi_{a,r}^I \phi_{a,r-\hat{j}}^I + \phi_{a,r}^I \phi_{a,r+\hat{j}}^I - \phi_{a,r}^R \phi_{a,r-\hat{j}}^R - \phi_{a,r}^R \phi_{a,r+\hat{j}}^R \\ &\quad + \epsilon_{ab} (\phi_{a,r}^R \phi_{b,r-\hat{j}}^I + \phi_{a,r}^R \phi_{b,r+\hat{j}}^I + \phi_{a,r}^I \phi_{b,r-\hat{j}}^R + \phi_{a,r}^I \phi_{b,r+\hat{j}}^R) \Big] \\ &\quad + \frac{i}{4\bar{m}} \sum_{\vec{x}, \tau} a^d \sum_{j=1}^d \sum_{a=1}^2 \left[4\phi_{a,r}^R \phi_{a,r}^I - \phi_{a,r}^R \phi_{a,r-\hat{j}}^I - \phi_{a,r}^R \phi_{a,r+\hat{j}}^I \right. \\ &\quad - \phi_{a,r}^I \phi_{a,r-\hat{j}}^R - \phi_{a,r}^I \phi_{a,r+\hat{j}}^R + \epsilon_{ab} (\phi_{a,r}^I \phi_{b,r-\hat{j}}^I + \phi_{a,r}^I \phi_{b,r+\hat{j}}^I \\ &\quad \left. - \phi_{a,r}^R \phi_{b,r-\hat{j}}^R - \phi_{a,r}^R \phi_{b,r+\hat{j}}^R) \right] \end{aligned} \quad (\text{A.59})$$

A.4.8 Action

We see from the above work that the full action can actually be calculated by summing many of the other observables.

$$\begin{aligned} S_{\text{lat}} &= S_{\mu} + S_{\nabla} - S_{\text{tr}} - S_{\omega} + S_{\text{int}} \\ &= \hat{N} + \phi^* \phi + \hat{T} - \frac{\bar{\omega}_{\text{tr}}}{2} \hat{V}_{\text{tr}} - \bar{\omega}_z \hat{L}_z + \bar{\lambda} \hat{V}_{\text{int}} \end{aligned} \quad (\text{A.60})$$

Complexification

As we have already developed a complexified expression for each of the observables that make up the action, we won't re-derive the expressions here. We can construct a complexified action from the observables already derived above.

A.4.9 Total Energy

Traditionally, in stat mech calculations, you can calculate the energy by taking a derivative of the partition function with respect to the inverse temperature, β . In lattice units, $\beta = N_{\tau} d\tau$, so we can

rewrite our lattice action in terms of β . We cancelled out factors of $d\tau$ and a , so we need to put those back in:

$$S_{\text{lat}} = \sum_{\vec{x}, \tau} a^d \left[\phi_r^* \phi_r - e^{d\tau\mu} \phi_r^* \phi_{r-\hat{\tau}} - \frac{d\tau}{2ma^2} \sum_{j=1}^d (\phi_r^* \phi_{r-\hat{j}} - 2\phi_r^* \phi_r + \phi_r^* \phi_{r+\hat{j}}) - \frac{m}{2} d\tau \omega_{\text{tr}}^2 r^2 \phi_r^* \phi_{r-\hat{\tau}} \right. \\ \left. + i d\tau \omega_z \left(\frac{x}{a} \phi_r^* \phi_{r-\hat{y}-\hat{\tau}} - \frac{x}{a} \phi_r^* \phi_{r-\hat{\tau}} - \frac{y}{a} \phi_r^* \phi_{r-\hat{x}-\hat{\tau}} + \frac{y}{a} \phi_r^* \phi_{r-\hat{\tau}} \right) + d\tau \lambda (\phi_r^* \phi_{r-\hat{\tau}})^2 \right] \quad (\text{A.61})$$

Note that only one term in the action has no dependence on $d\tau$, and it came from a derivative with respect to $d\tau$ **[NOTE: Possibly, you have to walk this back one more step... to before you combined terms to get the exponential. It may not make a big difference, and right now we're not very interested in this observable, but look into it.]**

If we multiply the whole thing by $1 = \frac{N_\tau}{N_\tau}$ (and use the same trick on the $d\tau\mu$ in the exponential), we can see where β appears:

$$S_{\text{lat}} = \frac{1}{N_\tau} \sum_{\vec{x}, \tau} a^d \left[N_\tau \phi_r^* \phi_r - N_\tau e^{\beta\mu/N_\tau} \phi_r^* \phi_{r-\hat{\tau}} - \frac{\beta}{2ma^2} \sum_{j=1}^d (\phi_r^* \phi_{r-\hat{j}} - 2\phi_r^* \phi_r + \phi_r^* \phi_{r+\hat{j}}) - \frac{m}{2} \beta \omega_{\text{tr}}^2 r^2 \phi_r^* \phi_{r-\hat{\tau}} \right. \\ \left. + i\beta \omega_z \left(\frac{x}{a} \phi_r^* \phi_{r-\hat{y}-\hat{\tau}} - \frac{x}{a} \phi_r^* \phi_{r-\hat{\tau}} - \frac{y}{a} \phi_r^* \phi_{r-\hat{x}-\hat{\tau}} + \frac{y}{a} \phi_r^* \phi_{r-\hat{\tau}} \right) + \beta \lambda (\phi_r^* \phi_{r-\hat{\tau}})^2 \right] \quad (\text{A.62})$$

We then take a derivative with respect to β , giving us:

$$\hat{E} = -\frac{1}{N_\tau} \sum_{\vec{x}, \tau} a^d \left[\mu e^{\beta\mu/N_\tau} \phi_r^* \phi_{r-\hat{\tau}} + \frac{1}{2ma^2} \sum_{j=1}^d (\phi_r^* \phi_{r-\hat{j}} - 2\phi_r^* \phi_r + \phi_r^* \phi_{r+\hat{j}}) + \frac{m}{2} \omega_{\text{tr}}^2 r^2 \phi_r^* \phi_{r-\hat{\tau}} \right. \\ \left. - i\omega_z \left(\frac{x}{a} \phi_r^* \phi_{r-\hat{y}-\hat{\tau}} - \frac{x}{a} \phi_r^* \phi_{r-\hat{\tau}} - \frac{y}{a} \phi_r^* \phi_{r-\hat{x}-\hat{\tau}} + \frac{y}{a} \phi_r^* \phi_{r-\hat{\tau}} \right) - \lambda (\phi_r^* \phi_{r-\hat{\tau}})^2 \right] \quad (\text{A.63})$$

This can be written in terms of our other observables, and we bring back our parameters in lattice units:

$$\hat{E} = -\frac{1}{N_\tau d\tau} \sum_{\vec{x}, \tau} a^d [\bar{\mu} (\phi_r^* \phi_r - S_\mu) - S_\nabla + S_{\text{tr}} + S_\omega - S_{\text{int}}] \\ = \sum_{\vec{x}, \tau} a^d \left[\frac{1}{N_\tau d\tau} \bar{\mu} \hat{N} + \frac{1}{N_\tau d\tau} \hat{T} - \frac{\bar{\omega}_{\text{tr}}}{2} \hat{V}_{\text{tr}} - \bar{\omega}_z \hat{L}_z + \bar{\lambda} \hat{V}_{\text{int}} \right] \quad (\text{A.64})$$

Complexification

Just as with the action, we can express the complexified total energy using our other observables.

A.4.10 Circulation

The circulation is defined as

$$\Gamma[l] = \frac{1}{2\pi} \oint_{l \times l} dx (\theta_{\tau, x+j} - \theta_{\tau, x}) \quad (\text{A.65})$$

$$\theta_{t, x} = \arctan \left(\frac{\text{Im}[\phi_{\tau, x}]}{\text{Re}[\phi_{\tau, x}]} \right). \quad (\text{A.66})$$

Given that our field, ϕ , is broken into 4 components ($\phi_{1/2}^{R/I}$), we need to rewrite this quantity in terms of those components:

$$\begin{aligned}
\phi &= \frac{1}{\sqrt{2}} (\phi_1^R + i\phi_1^I + i\phi_2^R - \phi_2^I) \\
\text{Re}[\phi_{\tau,x}] &= \frac{1}{\sqrt{2}} (\phi_{1,\tau,x}^R - \phi_{2,\tau,x}^I) \\
\text{Im}[\phi_{\tau,x}] &= \frac{1}{\sqrt{2}} (\phi_{1,\tau,x}^I + \phi_{2,\tau,x}^R) \\
\theta_{\tau,x} &= \arctan \left(\frac{\phi_{1,\tau,x}^I + \phi_{2,\tau,x}^R}{\phi_{1,\tau,x}^R - \phi_{2,\tau,x}^I} \right). \tag{A.67}
\end{aligned}$$

Note, we have the potential to encounter singularities here – in the extremely unlikely event that $\phi_{1,\tau,x}^R = \phi_{2,\tau,x}^I$, we will have a zero in the denominator. This probably won't ever occur, but we should take it into account when troubleshooting.

We need to convert our integral to a sum, in order to calculate it on a lattice. So we choose an $l \times l$ sub-section of the lattice centered around the middle and proceed around it in a clockwise fashion.

$$\begin{aligned}
\Gamma[l] &= \frac{a}{2\pi} \sum_{l \times l} (\theta_{\tau,x+j} - \theta_{\tau,x}) \\
&= \frac{a}{2\pi} \sum_{l \times l} \left[\arctan \left(\frac{\phi_{1,\tau,x+\hat{j}}^I + \phi_{2,\tau,x+\hat{j}}^R}{\phi_{1,\tau,x+\hat{j}}^R - \phi_{2,\tau,x+\hat{j}}^I} \right) - \arctan \left(\frac{\phi_{1,\tau,x}^I + \phi_{2,\tau,x}^R}{\phi_{1,\tau,x}^R - \phi_{2,\tau,x}^I} \right) \right] \tag{A.68}
\end{aligned}$$

where $\phi_{\tau,x+j}$ is the value of the field at the next site on the loop from $\phi_{\tau,x}$ for each point along the loop.

We can then average this value over the extent of our temporal lattice to produce a value with a mean and standard error.