

Wigner Crystal Collective tunneling - A theoretical investigation

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The documentation of the title's topic, Wigner crystal collective tunneling. Motivated by experiments, where in an effectively one dimensional system a wigner crystal for up to 7 electrons were observed. This work aims to investigate the phenomena from a theoretical point of view using ED, Instanton and DMRG techniques.

Usage: This note aims to document every major development in the project, explain the necessary 'new' physics (at least new for me), derive or proof mathematical concepts that the investigation is dependent upon, and be a somewhat self-contained material for me and possibly others during the research process.

Structure: The structure is as follows: Starting from elementary physics concepts that describes the environment that we are trying to understand, then developing the path integral tools along Feynman's book and Milnikov's work, these are followed by Monte-Carlo simulations, ED calculations and Polarization calculations, then ends with open questions, hopefully with some answers. The notes ends with the Appendix containing the necessary math, programming and other important materials.

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I. WIGNER CRYSTAL

II. PATH INTEGRAL FORMALISM

A. Free Particle

B. Harmonic Oscillator

C. One Particle Tunneling

1. One Particle Hamiltonian

2. Action Integral Calculation

3. Tunneling calculation in quartic potentials

III. EXPERIMENTAL CONSIDERATIONS

A. Modeling the Potential and Fitting

B. Polarization data

C. Scaling

IV. MANY BODY TUNNELING CALCULATIONS - INSTANTON

A. Quartic Hamiltonian model

1. Rescaling and Dimensionless Hamiltonian

B. Milnikov method

C. Classical Equilibrium Positions

D. Harmonic Oscillator Eigenfrequencies and Eigenmodes

E. Trajectory Calculation

F. Arc Length Parameterization

G. Exact Diagonalization (ED)

V. POLARIZATION

A. Classical Polarization Calculation

B. Polarization using ED

VI. OPEN QUESTIONS

Appendix A: Mathematics

1. Gaussian Integrals

$I(a)^2$, go to a polar coordinate representation by a simple substitution, then integrate over the polar angle ϕ and finally take the square root of the result.

$$I(a)^2 = \int_{-\infty}^{\infty} dx_1 \int_{-\infty}^{\infty} dx_2 e^{ax_1^2} e^{ax_2^2} \quad (\text{A.1})$$

$$= \iint_{-\infty}^{\infty} dx_1 dx_2 e^{a(x_1^2 + x_2^2)} \quad (\text{A.2})$$

Now one can go from $dx_1 dx_2$ to $dr d\phi$, by the $x_1 = r \cos(\phi)$ and $x_2 = r \sin(\phi)$. Meaning that $x_1^2 + x_2^2 = r^2$ replaces the exponent. Calculating the Jacobian for the change of the metric

$$J = \begin{vmatrix} \frac{\partial x_1}{\partial r} & \frac{\partial x_1}{\partial \phi} \\ \frac{\partial x_2}{\partial r} & \frac{\partial x_2}{\partial \phi} \end{vmatrix} = \begin{vmatrix} \cos(\phi) & -r \sin(\phi) \\ \sin(\phi) & r \cos(\phi) \end{vmatrix} = r \quad (\text{A.3})$$

$$I(a)^2 = \int_0^{\infty} dr \int_0^{2\pi} d\phi r e^{a(r^2)} \quad (\text{A.4})$$

$$= 2\pi \int_0^{\infty} dr r e^{a(r^2)} \quad (\text{A.5})$$

It is convenient to make another substitution $q = -r^2 \rightarrow dq = -2r dr$.

$$I(a)^2 = -2\pi \int_0^{\infty} dq \frac{1}{2} e^{-a q} \quad (\text{A.6})$$

$$= \frac{\pi}{-a} \quad (\text{A.7})$$

$$I(a) = \sqrt{I(a)^2} = \sqrt{\frac{\pi}{-a}} \quad (\text{A.8})$$

assuming that $\Re(a) \leq 0$

Problem A.2 (General Gaussian Integral).

2. Cauchy's Residue Theorem

3. Bessel Problem

Prove the following equality

$$\sum_{n=1}^{\infty} \frac{1}{n^2} = \frac{\pi^2}{6} \quad (\text{A.9})$$

Problem A.3 (Basel problem - Fourier series way). Let's consider first an arbitrary function $f(x)$. One could write the Fourier series of this function as

$$f(x) = \frac{a_0}{2} + \sum_{n=1}^{\infty} \left\{ a_n \cos\left(\frac{n\pi l}{L}\right) + b_n \sin\left(\frac{n\pi l}{L}\right) \right\}, \quad (\text{A.10})$$

where $l \in [l_i, l_f]$ and $L = l_f - l_i$. Let $f(x) = x^2$ and $l_i = -l_f = -\pi$ so that $L = 2\pi$. The coefficients can be calculated as

$$a_0 = \frac{2}{L} \int_{-\pi}^{\pi} f(x) dx = \frac{2}{\pi} \int_0^{\pi} dx x^2 = \frac{2}{3} \pi^2 \quad (\text{A.11})$$

Problem A.1 (Purely quadratic case). $I(a) = \int_{-\infty}^{\infty} dx e^{ax^2}$ A way to solve this integral is to introduce

$$\begin{aligned}
a_n &= \frac{2}{L} \int_{-\pi}^{\pi} dx f(x) \cos\left(\frac{n\pi 2x}{L}\right) \\
&= \frac{2}{\pi} \left(\frac{x^2 \sin(nx)}{n} \right) \Big|_0^{\pi} - \frac{2}{\pi} \int_0^{\pi} dx \frac{2x \sin(nx)}{n} \\
&= \frac{4(-1)^n}{n^2}.
\end{aligned} \tag{A.12}$$

Considering the problem at hand, consider the function as x^2 , so $b_n = 0$ because x^2 is even. The Fourier series then takes the form

$$\begin{aligned}
x^2 &= \frac{2\pi^2}{3 \cdot 2} + \sum_{n=1}^{\infty} \frac{4(-1)^n}{n^2} \cos\left(\frac{2n\pi x}{L}\right) \\
&= \frac{\pi^2}{3} + \sum_{n=1}^{\infty} \frac{4(-1)^n}{n^2} (-1)^n.
\end{aligned} \tag{A.13}$$

Choose x^2 to be equal to 0,

$$\pi^2 = \frac{\pi^2}{3} + \sum_{n=1}^{\infty} \frac{4}{n^2}. \tag{A.14}$$

Then subtract the a_0 term and divide by 4

$$\frac{\pi^2}{6} = \sum_{n=1}^{\infty} \frac{1}{n^2} \tag{A.15}$$

Problem A.4 (Complex Integral way). Consider the following integral:

$$I = \int_C \frac{1}{z^2} f(z) dz. \tag{A.16}$$

Let $f(z)$ be the Fermi function:

$$f(z) = \frac{1}{1 + e^{i\pi z}}, \tag{A.17}$$

then we have several first order poles at $z = \pm(2n+1) = p_n$ and a second order pole at $z = 0$.

The residue from the 1st order poles:

$$\text{Res}(f(z), p_n) = \lim_{z \rightarrow p_n} (z - p_n) f(z) = \frac{i}{\pi p_n^2}, \tag{A.18}$$

and from the 2nd order pole:

$$\text{Res}(f(z), 0) = \lim_{z \rightarrow 0} \frac{d}{dz} (z^2 f(z)) = \frac{-\pi i}{4}. \tag{A.19}$$

Writing now Cauchy's residue theorem [A 2](#)

$$\int_C g(z) dz = 2\pi i \sum \text{Res}(g(z)) \tag{A.20}$$

$$\int_C f(z) dz = 2\pi i \left(\frac{-\pi i}{4} \right) + 2\pi i \sum_{n=0}^{\infty} \frac{2i}{\pi(2n+1)^2} = 0 \tag{A.21}$$

$$\frac{\pi i}{4} = \sum_{n=0}^{\infty} \frac{2i}{\pi(2n+1)^2} \tag{A.22}$$

$$\frac{\pi^2}{8} = \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \tag{A.23}$$

$$= \frac{3}{4} \sum_{n=1}^{\infty} \frac{1}{n^2} \tag{A.24}$$

$$\frac{\pi^2}{6} = \sum_{n=1}^{\infty} \frac{1}{n^2} \tag{A.25}$$

Appendix B: Algorithms and Methods

1. Monte Carlo and Simulated Annealing

2. Minimalization by Nelder-Mead algorithm

Appendix C: Links, Data and other stuff

[\[1\]](#), [\[2\]](#)

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- [1] Anna Andereg, 2022, Example 1.
 - [2] Brenda Bradshaw, 2021, Example 2.