

# Project 2

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## 1 Introduction

## 2 Theory

Electrons in a confined, two dimensional harmonic oscillator potential with the given (idealized) Hamiltonian below is in quantum mechanics called quantum dots.

$$\hat{H} = \sum_{i=1}^N \left( -\frac{1}{2} \nabla_i^2 + \frac{1}{2} \omega^2 r_i^2 \right) + \sum_{i < j} \frac{1}{r_{ij}}$$

, [#eq:Hamiltonian]

where  $r_{ij} = |r_1 - r_2|$ , the distance between the electrons. Natural units ( $\hbar = c = e = m_e = 1$ ) are used and energies are in atomic units (a.u). The first term/sum of the hamiltonian is the harmonic oscillator part, well known from quantum mechanic. It is what's called the unperturbed part. Because electrons repel each other, a repulsion term (the second sum) is added. This term is what's called the perturbation of the system. The modulus of the positions of the electrons (for a given electron  $i$ ) as

$$r_i = \sqrt{r_{ix}^2 + r_{iy}^2}$$

.

The system will be utilized for closed shells, ie.  $N = 2, 6, 12$  and  $20$  electrons.

### 2.0.1 Wavefunction

The wavefunction for a two dimensional system with the Harmonic Oscillator potential is given by

$$\Phi_{n_x, n_y}(x, y) = A H_{n_x}(\sqrt{\omega}x) H_{n_y}(\sqrt{\omega}y) \exp \left[ -\frac{\omega}{2}(x^2 + y^2) \right]$$

where  $H_{n_x}$  are Hermite polynomials, and  $A$  is the normalisation constant. For the lowest lying state  $n_x = n_y = 0$  and hence the energy is  $\epsilon_{n_x, n_y} = \omega(n_x + n_y + 1) = \omega$ .

The energy of the ground state for two electrons without interaction, is simply the sum of the energies:  $\epsilon_{n_x, n_y} = 2 \times (0 + 0 + 1) = 2\omega$ .

The wavefunction for the unperturbed system is given by

$$\Phi(\mathbf{r}_1, \mathbf{r}_2) = C \exp \left[ -\frac{\omega}{2} (\mathbf{r}_1^2 + \mathbf{r}_2^2) \right]$$

where  $\mathbf{r}_i = \sqrt{r_{i_x}^2 + r_{i_y}^2}$ . The total spin in the ground state is simply zero as the two electrons living in the state is paired with opposite spins (eg.  $\pm 1/2$ ).

The ground state energy is given by the unperturbed system. Adding a perturbation/interaction will rise the energy. For the simplest system with two electrons, this perturbation can be found through perturbation theory, whilst for a higher number of particles, other measurements/actions must be taken to find the energy(??)

## 2.1 Local energy

By definition, the local energy is given by

$$E_l = \frac{1}{\Psi_T} \hat{H} \Psi_T$$

$\Psi_T$  is the trial wavefunction of the system. The Hamiltonian is given by eq. {??} and the trial wavefunction is

$$\Psi_T(\mathbf{r}_1, \mathbf{r}_2) = \Psi_1 * \Psi_2 = C \exp(-\alpha\omega(r_1^2 + r_2^2)/2) \exp\left(\frac{ar_{12}}{1 + \beta r_{12}}\right)$$

Where  $a = 1$  when the two electrons in question have anti-parallel spins and  $a = 1/3$  when the spins are parallel.  $\alpha, \beta$  are the variational parameters.

Hence, the local energy is shown to be ( see appendix)

$$E_L = 2\alpha\omega + \frac{1}{2}\omega^2(1-\alpha^2)(r_1^2 + r_2^2) - \frac{a}{(1 + \beta r_{12})^2} \left( -\alpha\omega r_{12} + \frac{a}{(1 + \beta r_{12})^2} + \frac{1 - \beta r_{12}}{r_{12}(1 + \beta r_{12})} \right) + \frac{1}{r_{12}}$$

[#eq:analytic-local-energy]

Eq. ?? is our analytic expression for the local energy of the two electron system.

The numerical local (kinetic) energy is calculated using the derivative of the velocity utilizing the two point approximation of the first derivative

$$\frac{dg(x)}{dx} \approx \frac{g(x + \Delta x) - g(x - \Delta x)}{2\Delta x}$$

Second derivative by three point approximation

$$\frac{d^2g(x)}{dx^2} \approx \frac{g(x + \Delta x) - 2g(x) + g(x - \Delta x)}{\Delta x^2}$$

$\Delta x$  is the stepsize which we let run towards zero. The error is proportional to  $(\Delta x^2)$ .

### **3 Method**

### **4 Results**

### **5 Discussion**

### **6 Conclusion**

## A Appendix

### A.1 Hermite polynomials

The Hermite polynomials are given by the following sequence

$$H_n(x) = c_n x^n + \dots + c_0 x^0$$

where the coefficients  $c_n$  are given by the sequence shown below [1]:

$$c_i = 1, 0, 2, -2, 0, 4, 0, -12, 0, 8, 12, 0, -48, \dots$$

## References

- [1] V. Jovovic, “A060821 - triangle t(n,k) read by rows giving coefficients of hermite polynomial of order n ( $n \geq 0$ ,  $0 \leq k \leq n$ ).” *The On-Line Encyclopedia of Integer Sequences*. Apr. 2001, Accessed: Apr. 27, 2021. [Online]. Available: <https://oeis.org/A060821>.