New Method to Study Ultra-cold Gases

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Bose-Einstein Condensates, an intriguing type of ultra-cold gas where all particles behave as one, and microscopic quantum effects are brought to light. They are notoriously difficult to describe and previous approach are either too simplified or too time consuming. Is there a better way?

All particles in nature appear in one of two flavors, either they are called bosons or fermions. These two flavors differ in one major way, bosons, in contrast to fermions, are allowed by the laws of nature to exist in the same state. This property of bosons is very peculiar, imagine having 10 special tennis balls that can all be placed in exactly the same spot, only taking up the space of a single tennis ball. This is essentially what happens when a gas of bosons is cooled down far enough, the bosons occupy the same state and behave as one, resulting in the formation of a *Bose-Einstein Condensate* (BEC).

Unfortunately, describing BECs theoretically in an attempt to better understand them, is no easy feat. Simplifications are necessary and typically one assumes that a large amount of bosons occupy exactly the same state, and only collide very weakly as to not bump bosons to other states. This approach results in the *Gross-Pitaevskii* (GP) equation which has proved instrumental over the years, accounting for tons of properties of BECs. Sadly, the GP equation fails when considering stronger collisions or BECs with smaller amounts of bosons, where impact of each boson plays a larger role. The GP equation has also failed to account for more delicate states such as the formation of water like BEC droplets, which were recently discovered.

Therefore, a lot of effort has been put towards building upon the GP equation to study more complicated BECs. This is usually done by allowing for bosons to occupy other states, which allows for stronger collisions and fewer bosons in the BEC. One such approach, is known as *Full Configuration Interaction* (FCI), which considers a large amount of particles and states. FCI is known to be accurate but is sadly very time consuming and is therefore only useful for a tiny amount of bosons.

This thesis explores one particular approach to build upon the GP equation by allowing for one or two bosons to occupy different states. We found great agreement with both FCI and the GP equation, verifying that our method works! Our method was also applied to more complicated systems such as the droplet BECs mentioned earlier, and although we were not able to correctly describe these systems, it did however show great promise for future research.