Project A: Rydberg Atoms

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I. Introduction to Rydberg atoms

In Bohr's original paper on hydrogen[1] he questioned why its that one could see hydrogen atoms with a principle quantum number **n** in a interval $n \leq 20$ (which had been discovered at the time) but very high lying levels hadn't been detected yet in the laboratory, making the comment that these atoms would be so large and weakly bound that they would immediately fall apart. Bohr thought that it would be necessary a very large volume, where there is a large amount of these atoms spreader very far apart to have a detectable signal. At the time Bohr could not have known that this is precisely the conditions that radio astronomers have when they look out into space and around 1965 these atoms with high lying levels where discovered. After further investigation it was denominated that a Rydberg atom is any atom with an electron in a state with a high principal quantum number, allowing a quantum mechanical treatment analogous to hydrogen [2]. Rydberg atoms are interesting systems to study due to their exaggerated properties such as a very sensitive response to electric and magnetic fields, long decay periods and the semi classical approximation of the electrons wave function to a orbit around the nuclei.

When considering the quantum mechanical description of any atom that has its outer most electron in a very high principal quantum number (typically $n \geq 20$) one can think of what is the total charge that this outer electron sees from the nucleus. Consider a atom with **Z** electrons, the nucleus has a charge $\mathbf{Z}e^+$ but from the point of view from the outer must electron sees a charge $\mathbf{Z}e^+$ with a cloud of electrons surrounding it with a total charge of $(\mathbf{Z}-1)e^-$ thus perceiving a total charge of e^+[3]. When the outer most electron is in a high principal number it perceives that it's part of a system analogs to the hydrogen atom. Using this insight we can learn a lot about Rydberg atoms using the quantum mechanical description of a hydrogen atom. From this one could wonder what could be the expected value for the radius $\langle r \rangle$ of outer most electron, how the energy E_n, its spacing ΔE_n and the expected value of the dipole moment $\langle \psi_i | \vec{d} | \psi_o \rangle$ are related. Using what is known from quantum mechanics one can write the following[4]:

$$\langle r \rangle \approx n^2 a_0 \ , \ \langle \Delta r \rangle \approx (2n-1)a_0 \tag{1}$$

$$E_n \approx \frac{1}{n^2} \ , \ \Delta E_n \approx \frac{1}{n^3} \tag{2}$$

$$\vec{d} = e\vec{r} \ , \ \langle \psi_i | \vec{d} | \psi_o \rangle = \langle \psi_i | e\vec{r} | \psi_o \rangle = e\langle r \rangle \langle \psi_i | \cos\theta | \psi_o \rangle \propto n^2 \tag{3}$$

with this, we can see that the radius increments with the same rate as does the dipole moment, with a squared dependence of the principal quantum number. The distance between to consecutive principal quantum numbers increments as a function of $2n-1$ which is a fairly large spacing between states. Also its worth to notice that the energy between levels, decreases very fast for consecutive large n, supporting the interpretation that the upper states are more tightly packed together. As an example, one of the largest n detection of Rydberg atoms in radio astronomy was a atom with an electron with $n = 350$, which implies $r \approx 6.5\mu m$, this might seem small, but for reference a red blood cell measures $8\mu m$ or consider the diameter of hair which is $50\mu m$. This

systems follow the laws of classical mechanics making it quite impressive that a single atom can be in a classical scale.

Considering the size of a Rydberg atom the next logical question would be to understand its lifetime or an analogs question, how long does this electron stay with its high principal quantum number. A precise mathematical deduction is done using Einstein A coefficient, which defines the spontaneous decay rate of a nl state to a lower $n'l'$ written as [3][5]:

$$A_{n'l',nl} = \frac{4e^2 w^3_{n'l',nl}}{3\hbar c^3} \left|\langle n'l'| \, r \, |nl\rangle\right|^2 , \; \tau_{nl} = \left[\sum_{n'l'} A_{n'l',nl}\right]^{-1} \tag{4}$$

notice that the A coefficient depends on the angular frequency w^3, which generally means that the transition with the highest frequency contributes the most to the radiative decay rate, therefore dominating the overall dependence on n. There are two case to consider for the decay of a electron, when $n'l'$ are small (close to the ground state) or when $n'l' \approx nl$ such as $n'l' \approx (n \pm 1)(l \pm 1)$. For the first case the decay of the electron can be calculated looking at the over lap of the wave functions for each corresponding state, if we considering that the frequency of the transition is constant. With the insight given by the radial distance previously discussed one can think that the over lap is minimum, thus producing a low probability for this decay, giving a life time $\tau_{nl} \approx n^3$. In the second case, decaying to a close state implies a change in the frequency of the transition this frequency contributes a factor of n^{-9}, taking that $\langle n-1 n-2| \, r \, |n, n-1\rangle \sim n^2$ the life time of the highest states scale as $\tau_{nl} \approx n^5$. In a statistical mixture of these two cases one gets $\bar{\tau}_{nl} \approx n^{4.5}$ giving us some insight in how these atoms can have such long lifetime even thought the outer electron is in a very high state[5]. A more practical explanation for the long lifetime can be thought threw the energy as was shown before, the higher the energy the more tightly packed are the energy levels thus making it necessary for the electron to jump through a lot of states, and for each there is the low probability of decay thus making it a long trip all the way down to the ground state.

II. Description of Experimental Set up to create Rydberg atoms

Now we are going to discuss a segment of a doctoral thesis - which involves the production of Rydberg atoms [6]. The experiment as seen in Fig.1 starts with preparation of the atoms in Magneto Optical Trap (MOT). After they are trapped, another laser system is used for cooling atoms to the ground state before turning in on to a Far-Off-Resonance Optical Trap (FORT). The monitoring of physical properties of the Rydberg atoms were accomplished by the FORT laser. Generally, to excite ground state atoms using laser light, can be done by using one-photon scheme, where the ground state is directly coupled to the Rydberg state, or multi-photon schemes using one or two intermediate states [7]. The excitation of Rydberg atoms in the experiment was done by two photon process with an intermediate transition.. Excitation of single photon requires stable light sources at $\lambda \approx 300nm$. This process must be equipped with dye laser that may emit fluorescence and exhibit laser gain, but this laser is more technically demanding and costly.

In the experiment Fig.1, two diode laser are used to generate a two photon transition. The diode lasers have a wavelength of 780 nm and 960 nm which are locked to different longitudinal modes of the same stable reference cavity. The laser with 960 nm wavelength has been amplified and frequency doubled to produce 480 nm beam. A 480 nm diode laser is more expensive and

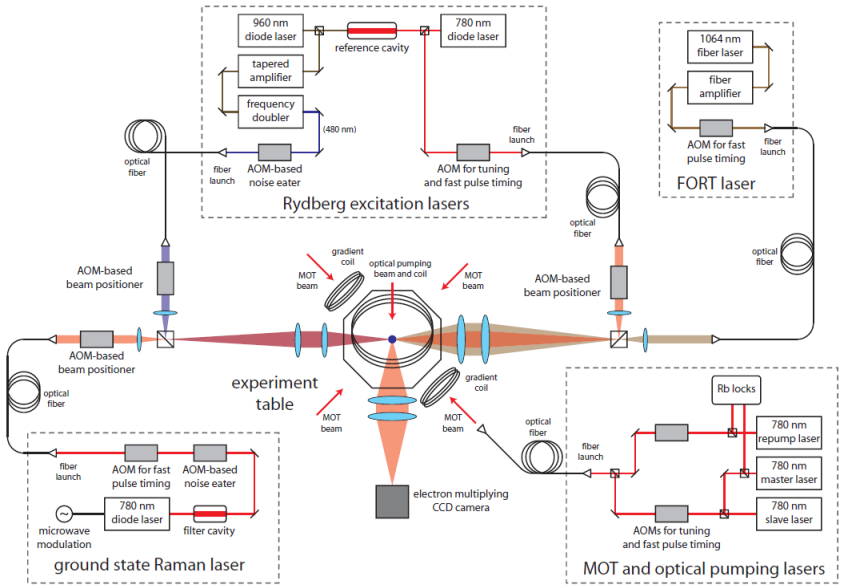


Figure 1: Experimental setup implemented to capture rubidium atoms and put them to a Rydberg state $n = 43$ [6]

complicated to produce than used a set up that doubled frequency of a reference laser. It is because there is tendency to be more susceptible to mechanical vibration and thermal influence. These two lasers are used in the experiment set up to drive a two photon excitation process for producing Rubidium Rydberg atoms. The 780 nm beam is used to excited the outermost electron from $5S_{1/2}$ state to a near-resonant $5P_{3/2}$ state, simultaneously 480 nm beam excited this electron to the Rydberg state $nD_{5/2}$a as shown in Fig.2. Having separate frequency operation is technically more advantages because single-frequency operation requires high power laser which have tendency to be more susceptible to mechanical vibration and thermal influence also high gain systems have high amplified spontaneous emission leading to spontaneous noise giving loss of gain.

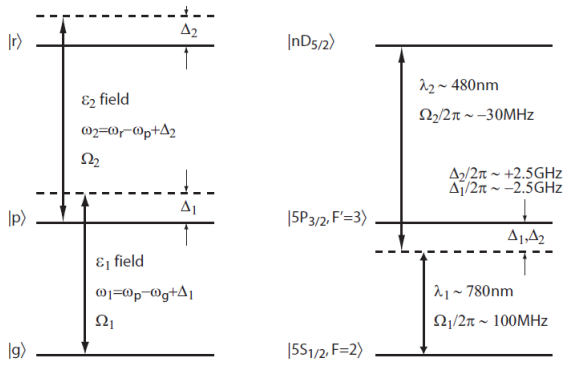


Figure 2: Energy level diagram used in Ref.[6] with he relevant fields and frequencies

III. Overview of general Laser systems

For many practical application, matching laser beam with another beam is necessary to achieve an efficient coupling. There are some methods to obtain the match mode such as coupled a beam from a laser into an optical fiber, injection locking which is mode of master laser has to be matched with slave laser, and a laser beam must be matched with optical resonator (cavity) which act as spatial or spectral filter [8]. In the laser cavity, the spatial mode is limited. Before entering the cavity, mode matching which is made up of some lenses should be performed to get the expected beam. In result, the beam could reach the cavity with maximum intensity and high power. This necessity of this mode matching optic is not only to create a good spatial overlap of the intensity profiles, but also for matching the optical phase which can leads amplitude profiles of two beam remain well matched during further propagation. The doubling cavity is used to double the frequency by putting a crystal which act as dielectric mirror coatings in a cavity. The intensity of the doubling frequency lasers is low, a stable and high intensity laser beam can be achieved when it is resonant. The crystal can be nonlinear material that rise second-harmonic generation. So, proper mode matching and a pump beam with high intensity can contribute to achieve power conversion efficiencies.[9].

One that can be consider to the most important system to the excitation process is a laser diode system. A laser diode system consists of a laser diode driver (cavity and gain medium), a laser mount (optical pump), temperature controller and in most application there is a doubling cavity which purpose is to pass the laser light produce in the diode driver threw a gain medium multiple times thus amplifying the incoming laser light after multiple oscillations inside of this doubling cavity [10]. In additional, optical isolators are used to protect a source from back reflections or signals that may occur. Back reflections cause to mode hop, amplitude modulate, or frequency shift that can damage a laser source. In high power applications, back reflections can cause instabilities and power spikes [11]. The essentially role of the diode laser system required well performance of the laser system that can be characterized by a power meter and spectrometer.

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