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# Optical Pumping in Xenon Atoms

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**Abstract:** We experimentally investigate the optimal production of metastable xenon using RF discharge techniques combined with optical pumping from an auxiliary state in xenon. This provides a robust platform for producing large long-term metastable densities.

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## 1. Introduction

Metastable noble gas atoms have applications ranging from fundamental physics experiments [1], to applications in plasma display panels [2], ultralow-power nonlinear optics [3], and rare gas lasers [4]. The production of high metastable densities is desirable in most of these applications. Although, relatively high densities in short time scales have been achieved using pulsed discharge techniques [2], the production of a long-term steady state densities is still challenging. Here, we investigate a recently proposed hybrid technique that combines RF excitations with optical pumping to produce a relatively high and steady state metastable density [5,6].

## 2. Metastable Xenon

An overview of relevant energy level diagram in xenon for our experiment is shown in panel (a) of Figure 1. The optical transition between the ground state  $|g\rangle$  ( $5p^6$ ) and the metastable state  $|m\rangle$  ( $6s[3/2]_2$ ) is forbidden by dipole selection rules. Therefore, we use an RF excitation to promote the neutral xenon atoms from the ground state  $|g\rangle$  to the metastable state  $|m\rangle$ . The key idea of this technique is that the same electrical discharge that creates population in  $|m\rangle$  also creates population in the auxiliary state  $|a\rangle$  ( $6s[3/2]_1$ ). The auxiliary population can then be optically pumped from  $|a\rangle$  to some upper state  $|u\rangle$ . Once populated,  $|u\rangle$  can decay to  $|m\rangle$  via spontaneous emission at 841 nm with a probability of 80%, or back to the auxiliary state  $|a\rangle$  with a probability of 20%. This will supplement the existing electrically-produced  $|m\rangle$  population. During this process, spontaneous emission from the dipole-allowed  $|a\rangle \rightarrow |g\rangle$  transition provides a source of resonant VUV photons at 147 nm that can be subsequently absorbed by nearby ground state atoms. Because the overall number of atoms that are excited by the RF discharge in a typical experimental set-up is much larger than the number of atoms in the cross-section of the NIR optical pumping beam, this effect gives a significant boost to the population that can be optical pumped from  $|a\rangle \rightarrow |m\rangle$ . The combination of all of these effects results in the strong optical enhancement to the electrically-produced population of  $|m\rangle$  that was first observed in [5]. Next, we perform the spectroscopic measurements of the transition from  $|m\rangle$  to an extra upper state  $|u'\rangle$  ( $6p[3/2]_2$  state) at 823 nm (probe) to characterize the metastable state ( $\text{Xe}^*$ ) density as a function of various experimental parameters.

## 3. Experimental Method and Results

The baseline  $\text{Xe}^*$  steady state density under optimized RF discharge conditions in our experiment is  $\sim 10^{11} \text{ cm}^{-3}$ , and the baseline density in the auxiliary state under the same conditions is  $\sim 10^{10} \text{ cm}^{-3}$ . We want to transfer as much of population at  $|a\rangle$  as possible into  $|m\rangle$ . This can be done by using (1) a large starting population at  $|a\rangle$  and (2) a strong optical pumping power at 916 nm. The panel (b) in Figure 1 shows the transferred population from  $|a\rangle$  to  $|m\rangle$  as a function of 916 nm optical pumping beam power for a variety of neutral xenon pressures. Here, we calculate the  $\text{Xe}^*$  density by measuring 823 nm (probe) transmission spectra with the 916 nm optical pumping beam turned on. In all cases, we saw a dramatic increase of  $\text{Xe}^*$  density as a function of increasing pump power ( $p_{\text{pump}}$ ). Thus, the goal of maximizing the metastable state density is achieved by using the neutral xenon pressure that maximizes the initial baseline values of  $\rho_m$  (and thus  $\rho_a$ ), and utilizing as much pump beam power as possible.

Panel (c) in Figure 1 illustrates this effect more clearly, where we plot the net increase in metastable state density,  $\Delta\rho_m$ , as a function of neutral xenon pressure, for several different values of  $p_{\text{pump}}$ . As can be seen from the plot,  $\Delta\rho_m$  is essentially flat over the range of xenon pressures from 15 mTorr to  $\sim 300$  mTorr, and its value determined solely by  $p_{\text{pump}}$ . The small drop-off in  $\Delta\rho_m$  values for pressures higher than  $\sim 300$  mTorr is most-likely due to insufficient initial  $\rho_a$  values in our set-up at higher pressures.

It is interesting to see that  $\Delta\rho_m$  exceeds the initial steady-state baseline auxiliary state density  $\rho_a$ . This is due to the fact that the effective lifetime of the metastable state is several orders of magnitude larger than the lifetimes

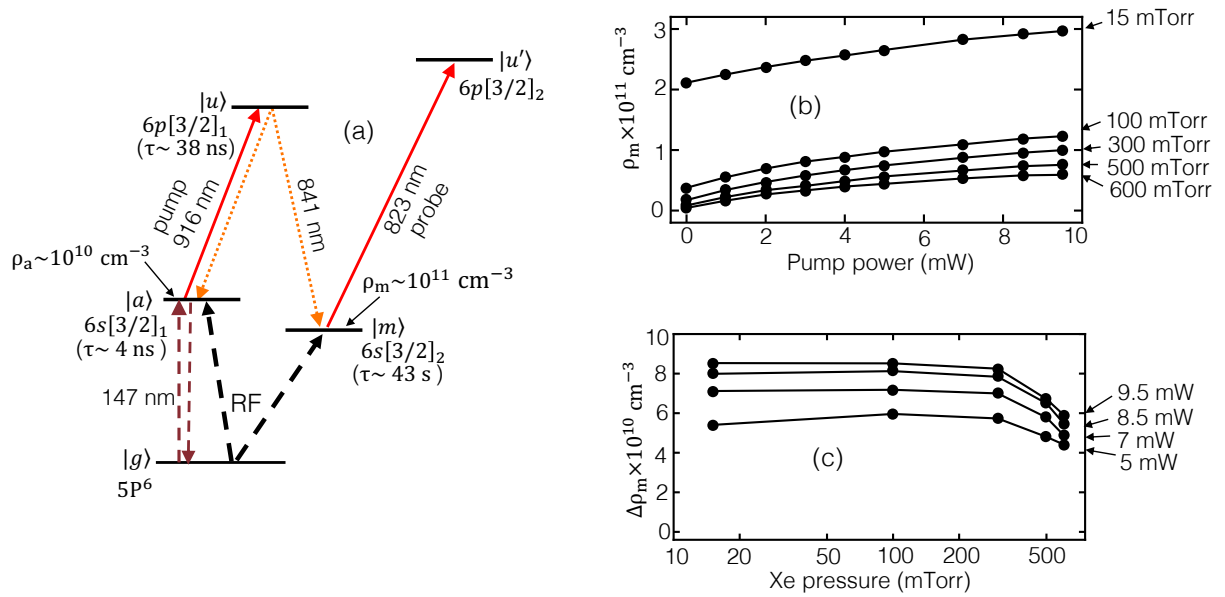


Fig. 1. Relevant energy level diagram and some key experimental results from [6]. (a) The goal of the work is to transfer as much population as possible from the ground state  $|g\rangle$  to the metastable state  $|m\rangle$ . We use an RF discharge and an optical pumping beam at 916 nm. (b) quantification of the desired increase in metastable state density,  $\rho_m$ , as a function of  $p_{\text{pump}}$  for several different neutral xenon pressures. (c) net change in metastable state density,  $\Delta\rho_m$ , as a function of neutral xenon pressure for 4 different values of pump beam powers. The data shows that  $\Delta\rho_m$  is fairly constant over a large pressure range, with a value largely determined by the pump power.

of the auxiliary state  $|a\rangle$  and upper state  $|u\rangle$  resulting in a desirable continuous-wave laser-pumped steady-state “build up” of population in the metastable state.

#### 4. Summary

In summary, we have investigated the experimental conditions needed to maximize the optical production of metastable xenon using a hybrid technique [5, 6]. Our results suggest that the technique can provide a robust method for producing relatively large long-term metastable state densities, which impact applications requiring high densities for longer continuous time scales [8].

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