Various ionization processes and ionization rate coefficients in the He-Cd^+ laser discharge

[1]Dr Chawhan A G , [2]Dr Keshatti S N

[1,2]Associate Professor,

[1] Department of Physics, LBS College,Dharmabad Dist.Nanded

[2] Department of Physics, Shri Shivaji College, Parbhani

Abstract : Ionization of atoms and ions plays vital role in lasers. In the present work ionization rate coefficients of atoms and ions of Helium and Cadmium have been obtained by using formulae proposed by Seaton and Wilson –White as a function of electron temperature. The results are presented in the form of graphs from which it is clear that initially ionization increases with the temperature and later on it saturates.

***Key Words* - ionization, recombination, ionization rate coefficient, electron temperature, collision.**

I. INTRODUCTION

The He- Cd^+ laser discharge consists of electrons and ions of different charges. These ions, atoms and electrons undergo a large number of collisions among themselves. There are two types of collisions in the discharge. In the first type of collision kinetic energy of particles is conserved. Such a collision is called as Elastic collision. These are responsible for heating of the laser plasma. In the second type of collision the kinetic energy of the incident electron gets converted into potential energy of the target particle Inelastic collision, as a result of this the total kinetic energy of the colliding particle is not conserved . This type of collision is called as Inelastic collision and it is responsible for excitation of atoms and ions.

It is well known that energy states in the laser discharge are populated by electron collision and depopulated by collision of ions with slow electrons. Due to collision, charge either increases or decreases by unity. Many times collision does not change the charge of colliding particle but changes the energy of the particles. When the ions of charge z are produce from the ions of charge z-1, the process is called as Ionization. When ions of charge z are produced from ions of charge z+1, the process is called as recombination.

II. IONIZATION PROCESSES

In the He- Cd^+ laser discharge, the helium (or cadmium) ions of charge z are produced by the process of ionization of helium (or cadmium) ions of charge z-1 and by the process of recombination of the helium (or cadmium) ions of charge z+1. The ionization may take place by electron impact if the incident electron has sufficient energy to detach an electron from the ion of charge z-1. The electron impact ionization of helium and cadmium species may summarized as follow

HeI + e -----He II +e

HeII + e -----HeI II +e

The process of electron impact ionization produces ions either in the ground or in the excited state.The ionization may take place due to absorption of photon by an ion having charge Z. The photons emitted during radiative recombination have sufficient energy to ionize the ions. The process of photo ionization may summarized as

HeI + hv ------ He II + e

HeII + hv ------ He III + e

Since there only two electrons in the 1S orbit of helium atom, thus autoionization process need not be considered.The above mentioned processes ionize the cadmium species also. The corresponding processes are written as

Electron impact ionization

CdI + e ------- CdII + e

CdII + e ------- CdIII + e

CdIII + e ------- CdIV + e

Autoionization

Cd I**--------- Cd I* + e

CdI I**--------- CdIII* + e

CdII I**--------- CdIV* + e

Phtotoionization

Cd I + hv ------ Cd II + e

CdI I + hv ------ Cd III + e

Cd III + hv ------ Cd IV + e

Stars on the species indicated the number of electrons in the excited orbit.In addition to these, the cadmium atom in the He-Cd^+ discharge may get ionized by

i) The Penning reaction ii) The Duffenduck reaction.

The Penning reaction

The process of ionization of atoms by collision with metastable atoms is called as Penning effect.

This reaction can be expressed as

A* + B --------A + B* + e

Where A* is an atom in the metastable state

B* is an atom in the excited state

The above reaction is energetically possible when ionization energy of atom B is lower than the excitation energy of the metastable atom A*.

The He-Cd^+ discharge consist of helium atoms in the triplet metastable states (Brown and Dunn [1], Goto et al [2], Mckenzie [3]). These atoms have sufficient energy to ionize and excite the cadmium atoms in various states. The energy level diagram of He and Cd illustrates the energy level coincidence between He*2^3S and He*2^1S and two Cd^+ $5S^2$ $^2D_{3/2}$ and $5S^2$ $^2D_{3/2}$ levels, it suggests an occurrence of He*-Cd Penning reaction of the type

$$He^*\ 2^3S + Cd\ 5S^2\ {}^1S_0 \text{ ------- } He\ {}^1S_0 + Cd^{++}\ 5S^2\ 2D_{3/2,\,5/2} + e + \Delta E \qquad (1)$$

Since the upper laser level have sufficient lifetime of about 0.5 ms whereas the lifetime of lower laser levels are only few nanoseconds. The selective pumping of Cd^+ $5S^2$ $^2D_{3/3,\,5/2}$ levels via Penning reaction in the equation (1) contributes to the laser emission at 441.6 and 325.0 nm.

Duffenduck reaction (Charge transfer reaction)

The process in which an ion having charge z in the ground state, when collide with the other ion having charge z' in the ground state, transfers its energy to the colliding partner and the other ion gets ionized This process of ionization and excitation of one ion and recombination of other ion is known as Duffenduck reaction or charge transfer reaction.

The majority of He-metal laser transitions are believed to be excited by charge transfer reaction which is expressed as

$A^+ + B$ ------- $A + B^{+*} + \Delta E$

where a single electron is transferred from an atom B in the ground state to an ion A^+ which is in the ground state.

Since charge transfer process is only two particle reaction, the only level of the atom B that can accept potential energy of the ion A^+ efficiently are the ones near the energy of the ion A^+. As B^{+*} is an excited ion, radiative decay of the lower lying energy states can occur which leads to the selective increase in the intensity of certain spectral lines of ions B^+.

The charge transfer reaction may be expressed as

$He^+\ {}^2S_{1/2} + Cd\ 5S^2\ {}^1S_0$ --------------- $He\ {}^1S_0 + Cd^{+*} + \Delta E$

Penning Ionization rate

The rate of production of CdII ions by penning reaction depends upon the density of neutral cadmium, density of metastable states and penning transfer coefficient P. The ionization rate by penning process can be expressed as

$$\frac{dN_{CdII}}{dt} = N_{HeI} * N_{CdI} * P$$

where P is a function of gas temperature, gas density and reaction cross section. The gas temperature governs the effective number of collisions between helium and cadmium atoms. The velocity of helium may be treated as an effective velocity. The rate coefficient P, the reaction cross section σ_p and the thermal velocity vHe are related as

$$P = \langle vHe\ \sigma_p \rangle$$

$$P = \frac{6.7*10^7}{86(\theta)^{3/2}} \int_0^\infty \sigma_p\ E \exp(-E/\theta)\ dE\ cm^3/sec$$

Where θ is the gas temperature in eV and E is the energy helium atom expressed in eV.

The penning excitation cross section σ_p is independent of the velocity colliding helium atoms [6]. And thus can be taken out of integration and we write

$$P = \frac{7.79*10^5}{86(\theta)^{3/2}} \int_0^\infty \sigma_p\ E \exp(-E/\theta)\ dE\ cm^3/sec$$

The above integral is a standard integral and substituting its value from standard integral table [11], the above equation reduces to

$$P = \frac{7.79*10^5}{86(\theta)^{\frac{3}{2}}}\ \sigma_p\ (\theta)^{3/2}$$

L D Shearer and Padovani [6] ,measured the total transfer cross section foe helium and cadmium atom by pulsed afterglow technique as $4.5x10^{-15}$ cm^2. If gas temperature is expressed in degree Kelvin , then penning transfer rate coefficient is expressed as

$$P = 7.79 \times 10^5\ \sigma_p\ (\theta)^{1/2}$$

We have calculated the penning transfer rate coefficient P as a function θ. The maximum value of gas temperature in the discharge tube is up to 1000 0 K. So the maximum value of θ is taken up to 20000K and the corresponding curve is as shown in the figure 1. The curve shows increase in the penning ionization rate coefficient with the increase in the gas temperature.

Electron impact ionization (EII)

An electron having energy more than the ionization energy of an electron revolving about an atom (ion or molecule), when collide with an atom (ion or molecule) having charge z, then it transfer the energy to the system and ionize the atom to the higher ionization states by detaching an electron from the atom (ion or molecule) into an ion of charge z-1.

The electron impact ionization rate coefficient S_z is a function of electron velocity distribution, electron energies and electron impact ionization cross section σ_z. Mathematically it is expressed as

$Sz = \langle v_e\ \sigma_z \rangle$

Wilson and White proposed [13] an empirical equation for the calculation of ionization rate coefficient, which is expressed as

$$S = J\ \frac{0.9*10^{-5}}{X^{\frac{3}{2}}} * \frac{\left(\frac{kT_e}{X}\right)}{\left(4.88+\frac{kT_e}{X}\right)} \exp\left(\frac{X}{kT_e}\right) cm^3/sec$$

Where X is ionization potential in eV, Te is electron temperature in degree Kelvin and J is the number of electron in the outer most orbits.

Lotz [14,15, 16] also proposed a semi empirical formula for the calculation of ionization rate coefficient which is expressed as

$$\sigma = \sum_i a_i q_i \frac{(ln\, {}^{E}/_{P_i})}{(Ep_i)} [1 - b_i] exp \left\{-c_i \left({}^{E}/_{P_i}\right) - 1\}\right] cm^2$$

Where E is the energy of the electron, P_i is the binding energy of the electron and q_i is the number of the electrons in the i^{th} sub shell. The constants a_i, b_i and c_i can be determined using experimental results. When the energy E of the colliding electron is very near to Pi, the factor E/Pi≈1. Hence

$$\sigma = \sum_i a_i q_i \frac{ln\left({}^{E}/_{P_i}\right)}{EP_i} [1 - bi] cm^2$$

For the electron energy very high compared to P_i, the factor E/P_i <<1 and thus above equation get modified to

$$\sigma = \sum_i a_i q_i \frac{ln\left({}^{E}/_{P_i}\right)}{EP_i}$$

This derivation of rate coefficient from cross section depends upon electron velocity distribution.

IV. RESULTS AND DISCUSSION

We have calculated ionization rate coefficient as a function of electron temperature of HeI and HeII for the electron temperature ranging from 0 to 10 eV by using Lotz formula and the results are displayed in figure 2. The ionization of HeI starts from T = 1.25 eV and goes on increasing up to T= 6 eV. Above this electron temperature the ionization rate gets saturated. The ionization of HeII starts at about T=2.6 eV and it increases as the electron temperature is increased up to 6 eV. For the electron temperature higher than 6 eV the ionization rate get saturated. For comparison between ionization rate coefficient, we have computed the IRC using Wilson and White formula and the results are displayed in the figure 2.The difference in the two values of ionization rate coefficient is about 1.5 to 2 at the higher temperature but this difference goes on decreasing as the electron temperature is decreased.

The ionization rate coefficient for CdI, CdII and CdIII are obtained using Wilson –White and Lotz formula as a function of electron temperature. The results are displayed in figure 3. The ionization of CdI starts from electron temperature 0.5 eV and increases up to 2 eV. Above this electron temperature it gets saturated. The ionization of CdII starts at about 1 eV and go on increasing up to 4.5 eV. Above this temperature it gets saturated. The ionization of CdIII starts at about T= 2.0 eV and increases as electron temperature is increased.

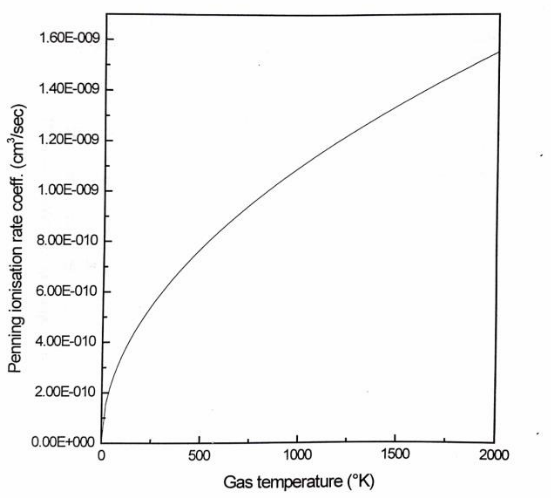

Fig1: Penning ionization rate coefficient as a function of gas temperature

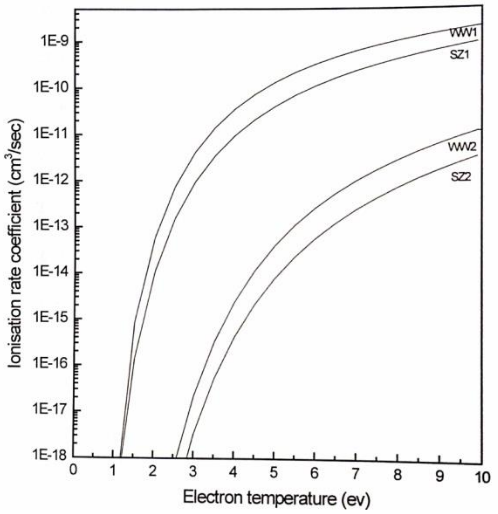

Fig2: Ionization rate coefficients of HeI(WW1,SZ1) and HeII(WW2,SZ2) as a function of electron temperature

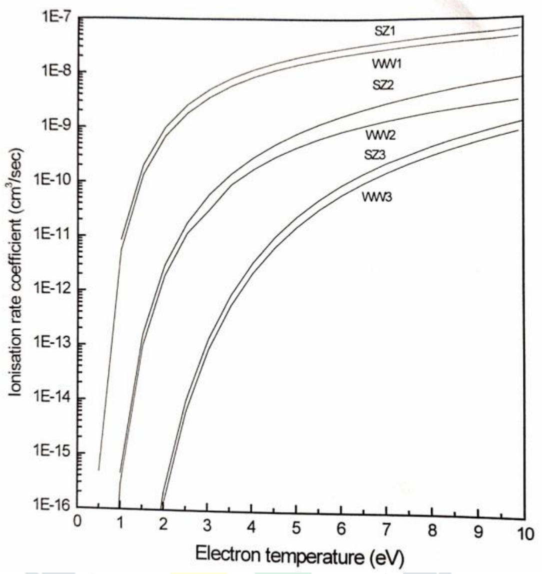

Fig2: Ionization rate coefficients of CdI(WW1,SZ1) , CdII(WW2,SZ2) and CdIII(WW3,SZ3) as a function of electron temperature

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