Electron excitation cross sections for the $1s_2$ and $1s_4$ levels in Ne

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The apparent and direct electron excitation cross sections of both the $1s_2$ and $1s_4$ levels of Ne are measured using laser-induced fluorescence. The experiment utilizes radiation trapping to maintain appreciable level populations. The direct excitation cross section for the $1s_2$ level has a peak value of 1.0×10^{-17} cm^2 at 65 eV; the direct excitation cross section for the $1s_4$ level has a peak value of 8.8×10^{-19} cm^2 at 65 eV.

Recently we have utilized laser-induced fluorescence to make the first accurate measurement of the electron excitation cross sections of the metastable $1s_3(^3P_0)$ and $1s_5(^3P_2)$ levels of Ne.[1,2] In this paper we report the first accurate measurement of the electron excitation cross sections of the $1s_2(^1P_1)$ and $1s_4(^3P_1)$ levels of Ne.

The measurements on the $1s_2$ and $1s_4$ levels are similar. For clarity we focus our discussion on the $1s_2$ level. Electron excitation produces $1s_2$ level Ne atoms, which radiate to the ground level with a lifetime of 1.65 ns.[3] At relatively high Ne density radiation trapping lengthens the effective lifetime of the $1s_2$ level so that an appreciable level population is maintained. Laser irradiation at 585.2 nm takes atoms from the $1s_2$ level to the $2p_1(2p^53p, J=0)$ level and the laser-induced $2p_1$-$1s_4$ fluorescence (540.1 nm) is used to determine the electron excitation cross section of the $1s_2$ level from threshold to 300 eV.

Figure 1 shows our apparatus. A 2-mm diameter, 0–200-mA, nearly monoenergetic electron beam (energy resolution of 0.5 eV) passes through 6–36 mTorr of Ne gas producing excited Ne atoms. The light emitted by the Ne is collected at right angles to the electron beam, analyzed by a 0.5-m monochromator and detected by a photomultiplier. The output of the photomultiplier serves as the input for a phase-sensitive detector. A cw dye laser intersects the electron beam along an axis that is perpendicular to both the electron beam and the light collection axis. The laser is chopped at a frequency of 720 Hz. A signal from the chopper serves as the reference signal for the phase-sensitive detector. The laser is set to the $1s_2\rightarrow2p_1$ wavelength using the optogalvanic effect in a Ne hollow cathode discharge. The output of the phase-sensitive detector is proportional to the difference between $2p_1\rightarrow1s_4$ fluorescence when the laser is on and when the laser is blocked off by the chopper. We denote this difference by $S_{on}-S_{off}$.

When the laser is tuned to the $1s_2\rightarrow2p_1$ absorption, the rate equations for the $1s_2$ level (labeled a) and the $2p_1$ level (labeled b) are

$$\frac{dn_a}{dt}=(nJ/e)Q_a-n_aA_{a\text{-eff}}+n_bA_{ba}+\sum_{\substack{j>a\\ j\neq b}}n_jA_{ja}-B_{ab}\rho n_a+B_{ba}\rho n_b\ , \qquad (1)$$

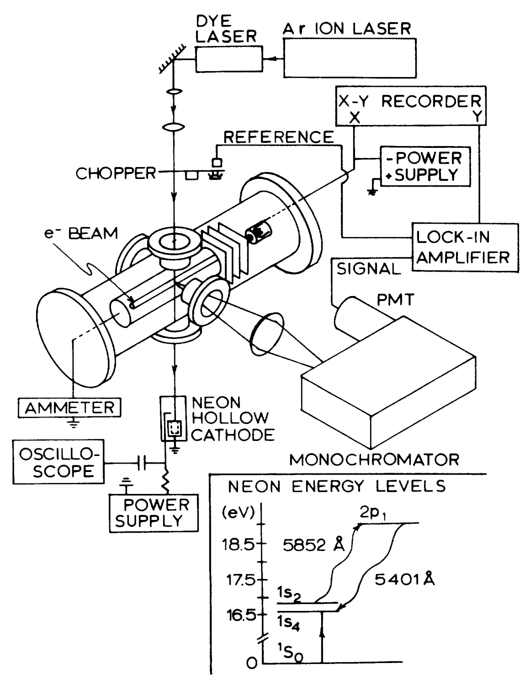

FIG. 1. A schematic diagram of our apparatus.

$$\frac{dn_b}{dt}=(nJ/e)Q_b-n_bA_b + \sum_{j>b} n_jA_{jb}-B_{ba}\rho n_b+B_{ab}\rho n_a \ , \qquad (2)$$

where n is the ground-level atom density, J is the electron current density, Q_i is the direct excitation cross section for level i, $A_{a\text{-eff}}$ is the reciprocal of the effective lifetime of level a, A_b is the reciprocal of the lifetime of level b, A_{ij} is the decay rate of level i into level j, B_{ab} and B_{ba} are the Einstein coefficients for induced absorption and emission, and ρ is the energy density in the laser beam. At the high atom densities used in our experiment radiation trapping causes $A_{a\text{-eff}}$ to be much less than the radiative decay rate of the $1s_2$ level, which is $A_a=6\times10^8\ \text{sec}^{-1}$. The cascade terms in Eqs. (1) and (2) can be rewritten in terms of optical cross sections, Q_{ij} defined as $n_jA_{ji}=(nJ/e)Q_{ji}$. The steady-state solution to Eqs. (1) and (2) is

$$n_{b\text{-on}}=\frac{k[Q_b^A+\gamma(Q_a^A-Q_{ba})]}{[A_b+B_{ba}\rho-\gamma(A_{ba}+B_{ba}\rho)]} \ , \qquad (3)$$

where $k=(nJ/e)$,

$$\gamma=B_{ab}\rho/(A_{a\text{-eff}}+B_{ab}\rho) \ ,$$

and where the apparent cross sections Q_a^A and Q_b^A are given by

$$Q_a^A=Q_a+\sum_{j>a} Q_{ja}$$

and

$$Q_b^A=Q_b+\sum_{j>b} Q_{jb} \ .$$

The apparent cross section is the direct cross section plus the sum of the cascade contributions. The subscript "on" indicates the laser is on. When the laser is blocked off we set $\rho=0$. This gives

$$n_{b\text{-off}}=(kQ_b^A)/A_b \ . \qquad (4)$$

It has been shown in Refs. 1 and 2 that $S_{\text{on}}-S_{\text{off}}$ is proportional to $\beta n_{b\text{-on}}+(1-\beta)n_{b\text{-off}}$, where β is a constant determined by the time average of the laser properties. Using Eqs. (3) and (4) and using $g_aB_{ab}=g_bB_{ba}$ we obtain

$$S_{\text{on}}-S_{\text{off}}\propto\frac{\beta k\gamma(Q_a^A-g_aA_{a\text{-eff}}Q_b^A/g_bA_b)}{A_b+B_{ba}\rho-\gamma(A_{ba}+B_{ba}\rho)} \ .$$

At a given laser intensity $S_{\text{on}}-S_{\text{off}}$ is proportional to $(Q_a^A-g_aA_{a\text{-eff}}Q_b^A/g_bA_b)$. Since at low density $A_{a\text{-eff}}=A_a=6\times10^8\ \text{sec}^{-1}$ and $A_b=7\times10^7\ \text{sec}^{-1}$ the value of $S_{\text{on}}-S_{\text{off}}$ is determined by both Q_a^A and Q_b^A. As the ground-level atom density increases radiation trapping reduces the value of $A_{a\text{-eff}}$ so that $S_{\text{on}}-S_{\text{off}}$ is determined largely by Q_a^A. We calculate using the theory of Holstein that for our geometry at a ground-level density of 1.2×10^{15} atoms/cm (corresponding to a pressure of 36 mTorr) the radiation trapped lifetime is long enough that $A_{a\text{-eff}}\sim10^6\ \text{sec}^{-1}$. Examination of the optical cross sections measured by Sharpton *et al.*[4] show that Q_b^A is about 0.6 of the cascade cross section into the $1s_2$ level at 100 eV. Thus Q_a^A is larger than Q_b^A by more than a factor of 2. Since $g_a/g_b=3$ we estimate that

$$(g_aA_{a\text{-eff}}Q_b^A/g_bA_b)<0.03Q_a^A$$

at $n=1.2\times10^{15}$ atoms/cm^3. Hence $S_{\text{on}}-S_{\text{off}}$ is taken to be proportional to Q_a^A. An absolute Q_a^A is obtained by normalizing $S_{\text{on}}-S_{\text{off}}$ at 300 eV to be equal to the sum of the measured cascades plus the value of Q_a obtained as follows. Fajen[5] has calculated Q_a using the Born approximation. The calculated Born cross sections vary as $\ln E/E$ (E is the incident electron energy) for energies above 100 eV. In the $\ln E/E$ region the Born cross sections are proportional to the square of the same dipole matrix elements used in the lifetime calculation. With the same set of wave functions used for the Born cross section, Fajen calculated a lifetime for the $1s_2$ level that is 36% larger than the experimental value of 1.65 ns.[3] Thus we correct the Born cross sections of Ref. 5 by scaling them by the ratio of the measured lifetime to the calculated lifetime. We believe that the scaled Born cross sections are satisfactory for use in calibration. Normalizing at 300 eV we find the Q_a^A agrees well with the measured cascades plus the Born approximation for energies down to 200 eV. This supports the validity of our normalization at 300 eV. The direct cross section is obtained at energies lower than 300 eV by subtracting the cascades previously measured by Sharpton *et al.*[4] from the normalized Q_a^A.

Fig. 2(a) shows both the apparent and direct electron excitation cross sections for the $1s_2$ level of Ne as a function of the energy. The maximum value of Q_a is 1.0×10^{17} cm^2 at an energy of 65 eV. We estimate that the relative uncertainty in the energy dependence of Q_a^A is 10%. The absolute uncertainty in Q_a^A depends on the accuracy of the scaled Born cross sections. The quoted uncertainty in the measured lifetime of the $1s_2$ level is 10%.[3] Also as discussed in Ref. 3 the lifetime of the $1s_2$ level presented in Ref. 3 is in excellent agreement

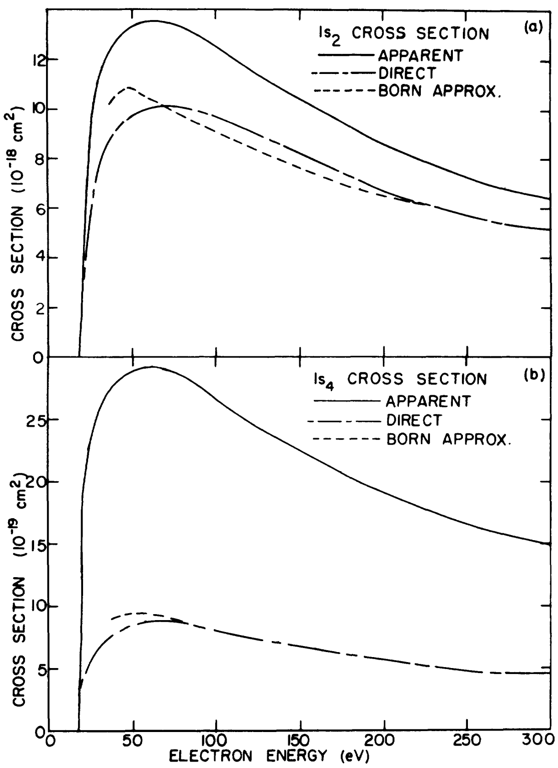

FIG. 2. (a) The apparent and direct electron excitation cross sections for the $1s_2$ level of Ne. Also shown is the Born approximation for the direct cross section. (b) The apparent and direct electron excitation cross sections for the $1s_4$ level of Ne. Also shown is the Born approximation for the direct cross section.

with earlier measurements. Using these results we conclude that the absolute uncertainty in Q_a^A is about 20%. The uncertainty in Q_a^A and the uncertainty in Sharpton's cascade measurements lead to an uncertainty in Q_a of about 28%.

Finally, we note that the signal $S_{\rm off}$ increases linearly with the ground-level Ne atom density. The value of $(S_{\rm on}-S_{\rm off})/S_{\rm off}$ increases from nearly zero at low Ne atom density to about 0.2 at a density of 1.2×10^{15} atoms/cm^3, where radiation trapping is important. The variation of $(S_{\rm on}-S_{\rm off})/S_{\rm off}$ as a function of the ground-level atom density is faster than linear as is expected with radiation trapping.

We have also obtained the apparent and direct electron excitation cross sections of the $1s_4$ level of Ne using the same methods as for the $1s_2$ level. The Born cross sections for the $1s_4$ level given in Ref. 5 are scaled according to the measured lifetime of that level (20.5 nsec).[3] The apparent and direct cross sections obtained are shown in Fig. 2(b). The peak value of the direct cross section is 8.8×10^{-19} cm^2 at 65 eV. The relative uncertainty in Q_a^A is about 10%. The absolute uncertainty in Q_a^A depends on the accuracy of the $1s_4$ lifetime. As discussed in Ref. 3 the measurements of the $1s_4$ lifetime fall into two groups, one at about 20 nsec and the other at about 30 nsec. We have used the recent value of 20.5 nsec since the measurements upon which it is based seem free of difficulties associated with cascades.[3] The quoted uncertainty in the $1s_4$ lifetime is 7.3%. With this uncertainty we estimate that the absolute error in Q_a^A is about 20% and the uncertainty in Q_a is about 28%. Nevertheless, if further studies show that the correct value of the $1s_4$ level lifetime is 30 nsec, the values of Q_a^A will be reduced by 23% from the values shown in Fig. 2(b).

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