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Excitation of H Atoms to the $n = 3$ States by the Impact of 10- to 35-keV Ground-State H Atoms on He, Ne, Ar, H_2, O_2, and N_2 †

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Absolute cross sections have been measured for the excitation of hydrogen atoms to the 3*s*, 3*p*, and 3*d* states by the impact of ground-state hydrogen atoms on He, Ne, Ar, H_2, O_2, and N_2 in the energy range from 10 to 35 keV. In this energy range the cross sections for the different angular momentum states are generally the same order of magnitude (10^{-18} cm^2). Excitation to the *s* state is more competitive with the *p*-state excitation at the $n=3$ level than at the $n=2$ level. Excitation to the 3*d* state is not as likely as excitation to the 3*s* or 3*p* states. Cross sections for the production of Balmer α radiation have been computed. Polarization fractions for the $3d \rightarrow 2p$ radiation have also been measured.

INTRODUCTION

There have been several measurements of the collisional excitation of fast ground-state hydrogen atoms by impact on gases. Excitation to the $n=2$ states has been studied for impact on the rare gases,[1–4] H_2,[5] N_2,[6,7,4] and O_2.[6] Excitation to the 3*s* states has been measured for impact on N_2.[8] Excitation to the $n=2$ and $n=3$ level has been treated theoretically for impact on H by Bates and Griffin.[9] Levy has recently treated excitation to the $n=2$ states for impact on the rare gases.[10]

This investigation reports measurements on the excitation to the 3*s*, 3*p*, and 3*d* states in the energy range from 10 to 35 keV for impact on He, Ne, Ar, H_2, O_2, and N_2.

APPARATUS AND ANALYSIS

The apparatus is similar to that used in the study of excitation to the 3*s* state by impact on N_2.[8] The collimation of the beam was increased for this experiment so that the beam emerges from the 1/16-in.-diam exit aperture of the collision chamber with only minimum interaction with the aperture edges.

The neutral beam density was measured by secondary electron emission from a nickel target. Calibration was accomplished by comparing with a proton beam at the same energy. The efficiency for secondary emission for neutral impact was taken to be 1.09 times that of protons in this energy range.[11] Two collision chamber lengths were used to check the excited atom buildup,[8] 5 and 8 cm. The final data were obtained using the shorter chamber. The 9558B EMI photomultiplier recorded the intensity of the Balmer α emission as a function

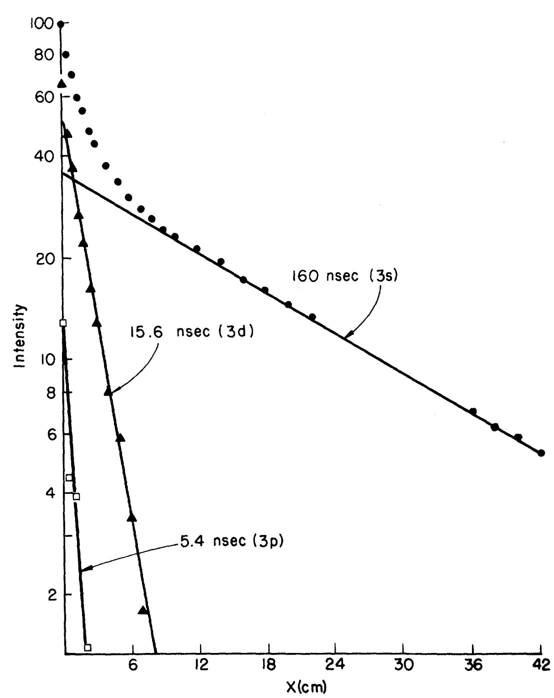

FIG. 1. Decay of H_α light from hydrogen atoms emerging from a collision chamber filled with Ne as a target gas (chamber length 5 cm). The distance (×) is measured from the exit aperture. The 3*d* decay is obtained by subtracting the long-lived 3*s* decay from the total decay curve circles, and the 3*p* decay is obtained by subtracting the longer-lived 3*d* from the remainder.

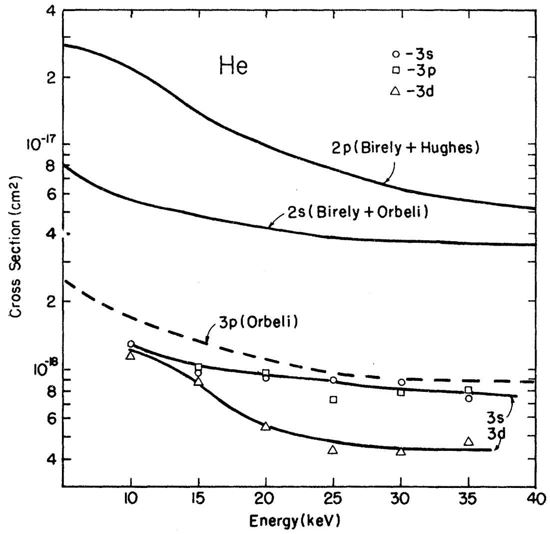

FIG. 2. Hydrogen-atom impact on He. The $3p$ Orbeli curve is taken from Ref. 1. The $2p$ curve below 25 keV is taken from Ref. 2, while the segment above 25 keV is taken from Ref. 4. The $2s$ curve below 25 keV is taken from Ref. 2, while the segment above 25 keV is taken from Ref. 1 and normalized to Ref. 2 at 25 keV.

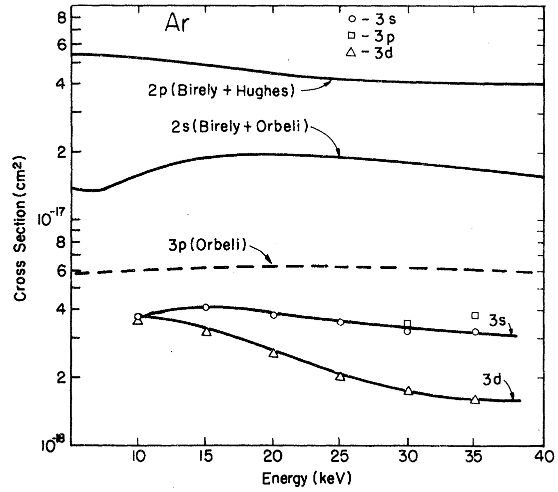

FIG. 4. Atom impact on Ar. See caption for Fig. 2.

of distance from the exit aperture of the collision chamber. The analysis of the resulting decay curve is identical to that used in the measurement of electron capture into the $n = 3$ level by proton impact on gases.[12] The photocathode was masked to accept optical emissions from a 1-cm-long segment of the beam. The photocathode surface had previously been mapped to obtain a reasonably constant spatial sensitivity.[12]

Optical calibration was established at 25 keV by comparing the signal from a point on the decay curve, where only $3s$ radiation remained, to that obtained when protons passed through the collision chamber. The resulting relative cross section was normalized to the $3s$ proton cross section.[12]

The polarization of the H_α light is a function of the distance measured from the exit aperture of the collision chamber. It is possible, in principle, to determine the polarization of both the $3p \rightarrow 2s$ and $3d \rightarrow 2p$ radiations by making polarization measurements at two different points along the H_α decay curve.[13] In practice, the uncertainties in the $3p \rightarrow 2s$ polarization determination are so large that they become meaningless. It is, however, possible to get meaningful polarization data for the $3d \rightarrow 2p$ transition. The $3d$ cross section values

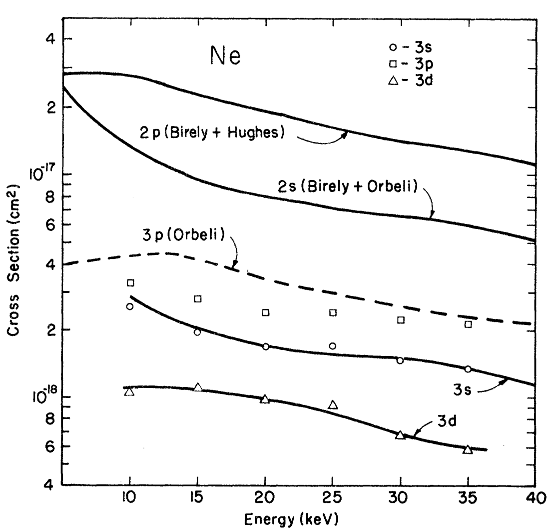

FIG. 3. Hydrogen-atom impact on Ne. See caption for Fig. 2.

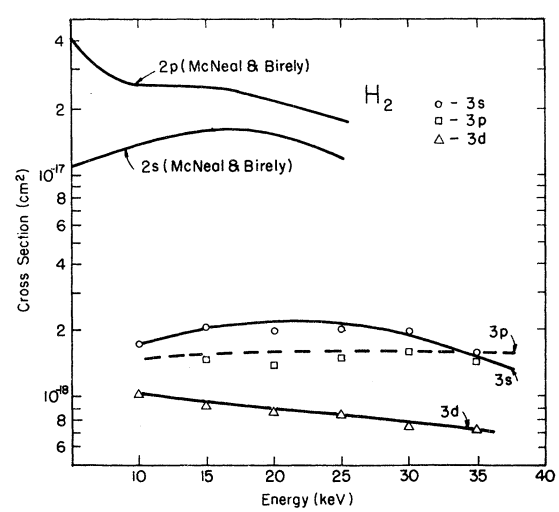

FIG. 5. Atom impact on H_2. The $2s$ and $2p$ excitation is taken from Ref. 5.

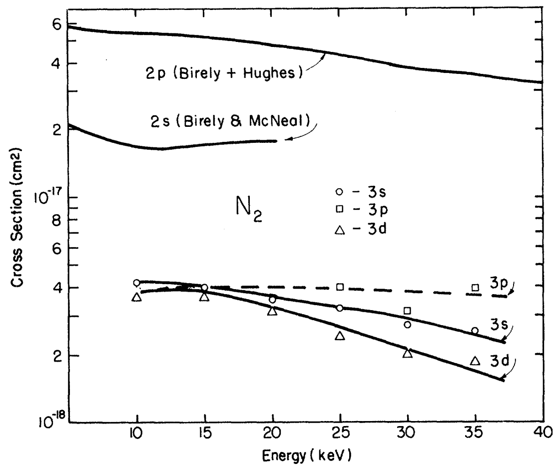

FIG. 6. Atom impact on N_2. The 2*s* cross sections are from Ref. 6. The 2*p* curve below 20 keV is from Ref. 6, while the segment above 20 keV is from Ref. 4.

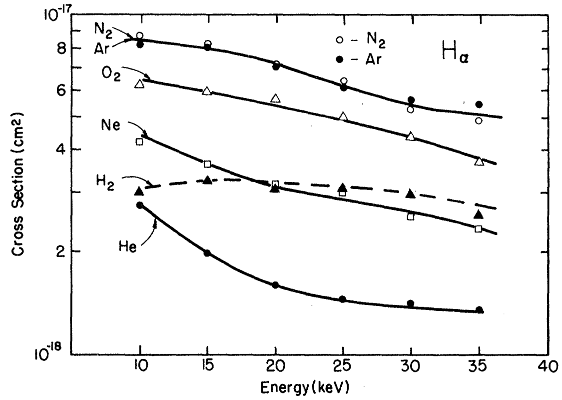

FIG. 8. Total cross sections for the production of Balmer α radiation.

presented here contain the polarization correction.

Figure 1 shows the analysis of 10-keV atom impact on Ne, collision chamber length of 5 cm. The curve demonstrates the difficulty at low energies in determining 3*p* information. Only 12% of the 3*p* decay goes via Balmer α. It is a small part of the signal and is obtained after subtracting the 3*s* and 3*d* decays. It is especially difficult at low energies where the 3*p* decay length (velocity times radiative lifetime) is very short (about $\frac{3}{4}$ cm at 10 keV) and where the longer-lived 3*s* and 3*d* state decay is enhanced. However, it is possible to obtain meaningful 3*p* measurements. Figures 2 and 3 show good comparisons between our method and the fundamentally more accurate method of simply measuring the L_β ($3p \rightarrow 1s$) radiation used by Orbeli *et al.*[1] for impact on He and Ne, respectively. Figure 4 includes a comparison of our 3*p* measurements with Orbeli for impact on Ar. We were unable to reproduce the Orbeli result for this gas. Our apparent cross sections for 3*p* excitation systematically decreased with energy. Since our confidence in the 3*p* measurements is limited, we decided to ignore the 3*p* measurements if the apparent 3*p* radiation represented less than 10% of the total H_α light at the exit aperture. Thus omission of 3*p* points from the cross-section plots implies that the analysis indicated that the 3*p* radiation was less than 10% of the total light at the aperture.

Reproducibility of the published data is as follows: 3*s*, about ± 10%; 3*d*, about ± 15%; and 3*p*, about ± 75%.

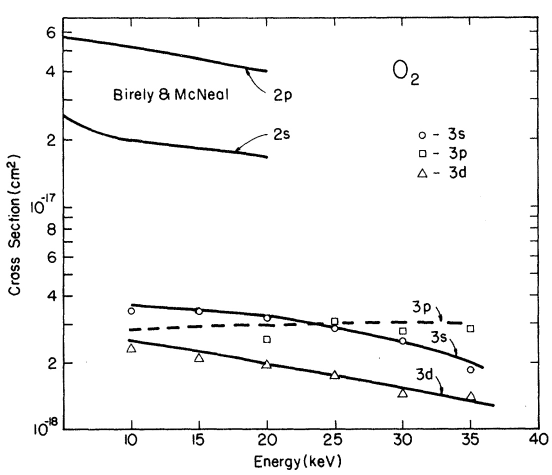

FIG. 7. Atom impact on O_2. The 2*s* and 2*p* cross sections are taken from Ref. 6.

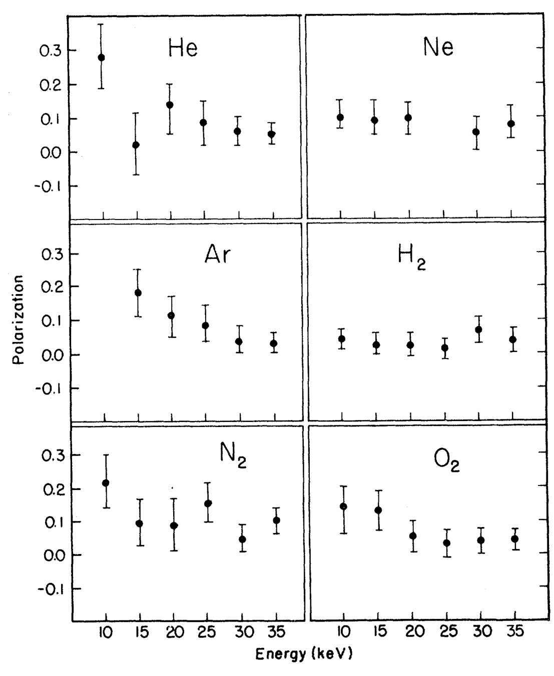

FIG. 9. Polarization fractions for the $3d \rightarrow 2p$ radiation.

RESULTS

Figures 2–7 show the results for impact on He, Ne, Ar, H_2, N_2, and O_2. Also plotted are $n = 2$ measurements taken from the literature. The magnitude of the 3*s*, 3*p*, and 3*d* cross sections are all comparable for any given gas. Generally, the 3*d* cross sections are smaller than the corresponding 3*s* and 3*p* cross sections. The *s*-state excitation seems more competitive with the *p*-state excitation at the $n = 3$ level than at the $n = 2$ level.

The ratio of 2*s* to 3*s* excitation is quite consistent from rare gas to rare gas and independent of the energy. The 2*s*-to-3*s* ratio is about 4.5 for impact on He, Ne, and Ar at all energies. Cross sections for 2*s* excitation are available to about 25 keV for impact on H_2, N_2, and O_2. The 2*s*-to-3*s* ratio is about 5.5 at 25 keV for impact on H_2, while it is about 5 at 20 keV for impact on N_2 and O_2.

The ratio of 2*p*-to-3*p* excitation fluctuates much more from gas to gas and from energy to energy. In the case of impact on He, this ratio is about 13 at 10 keV and about 6 at 35 keV. The ratio is fairly independent of energy for impact on Ne and remains about 6. For Ar the ratio is about 8. (The 3*p* cross section is taken to be about 5×10^{-18} cm^2 for Ar, which gives some weight to our 3*p* measurements at 30 and 35 keV and reduces the Orbeli measurement by 20%.) For impact on H_2 at 25 keV, the 2*p* excitation is about an order of magnitude larger. For impact on N_2 and O_2, the 2*p* excitation appears to be an order of magnitude larger than 3*p* excitation.

Figure 8 shows the total H_α cross sections which are synthesized from the 3*s*, 3*p*, and 3*d* cross sections. These cross sections are those that one would measure for the production of H_α radiation inside the collision chamber at a point sufficiently far from the entrance aperture to ensure equilibrium conditions. The excitation H_α cross sections are generally comparable to those for the production of H_α by charge transfer.[12]

The polarization fractions for the $3d \rightarrow 2p$ radiation are presented in Fig. 9. The polarization fractions are defined as $P = (I_\parallel - I_\perp)(I_\parallel + I_\perp)^{-1}$ where $I_\parallel$ is the intensity of the light with the electric vector parallel to the axis of quantization (atom beam axis) and $I_\perp$ is the intensity of the light with the electric vector perpendicular to the axis. They are all positive but generally decrease in value as the energy is increased. The errors are large and therefore it is difficult to make quantitative statements. Dose *et al.*[14] have measured positive polarization for $2p \rightarrow 1s$ radiation produced by atom impact on the rare gases. Positive polarization generally implies that the component of linear momentum, imparted in the collision process, along the beam axis is large compared to the component in the perpendicular direction.[15] For very high-velocity impact it is expected that the momentum transfer will be more in the perpendicular direction which will produce negative polarization.[15] The Born approximation predicts negative polarization in $2p \rightarrow 1s$ radiation for high-velocity impact of hydrogen atoms on He.[16]

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