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Balmer-line emission from low-energy H impact on Kr and Xe

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Absolute cross sections for the emission of Balmer-α and Balmer-β radiation have been measured for H+Kr and H+Xe collisions. Measurements were made for H-atom energies from 2.5 to 0.04 keV. The polarizations of the emitted radiations were also determined and, for H-atom energies above 0.2 keV, the contributions to these emissions from decay of the long-lived 3*s* and 4*s* excited states of hydrogen were resolved. The results are discussed in comparison with similar data for H-atom impact on the other rare-gas atoms.

I. INTRODUCTION

In earlier papers, absolute cross sections for the emission of Balmer-α (H_α) and Balmer-β (H_β) radiations resulting from H-atom impact on Ar targets,[1] N_2 and O_2 targets,[2] He and H_2 targets,[3] and Ne targets[4] were reported for H-atom energies from 2.5 to 0.04 keV. Measurements of the polarizations of the emitted radiations were also presented. For H-atom energies above 0.2 keV, the contributions to these total emissions from the $3s \rightarrow 2p$ and $4s \rightarrow 2p$ hydrogenic transitions were separated from the other $np \rightarrow 2s$ and $nd \rightarrow 2p$ emission components. This was accomplished by observing the growth in the measured photon signals as a function of distance into the target cell and employing an analysis based upon the relatively long radiative lifetimes of these excited *ns* states.[5]

This paper reports similar data for H-atom impact on Kr and Xe targets. The experimental techniques used to make the measurements were identical to those employed earlier,[1] and will not be reviewed here. The H-atom beam used for the studies has also been described elsewhere,[6] and the absolute calibration of the photon detector used can again be traced to the accurately known cross sections for $n\,^1S \rightarrow 2\,^1P$ emissions resulting from electron-impact excitation of He atoms.[7]

II. RESULTS AND DISCUSSION

The measured H_α and H_β emission cross sections are shown in Figs. 1(a) and 1(b), respectively, where the data for H+Kr collisions are presented as solid symbols and solid-line curves and those for H+Xe collisions as open symbols and dashed-line curves. Also shown for H-atom energies above 0.2 keV are the components of these total emissions resulting from decay of the excited states labeled. The total emission and the $(np \rightarrow 2s)+(nd \rightarrow 2p)$ emission cross-section values plotted are typically uncertain by about $\pm 15\%$, except for H_β emission from H+Xe collisions. Here, some of the observed photon signal may have come from the 486.2-nm emission line of Xe^+, which would be transmitted by the interference filter used to isolate H_β radiation.[1] For H-atom energies above 0.4 keV, the $3s \rightarrow 2p$ emission cross-section values are typically uncertain by $\pm 20\%$, and those for $4s \rightarrow 2p$ emission by $\pm 30\%$. At lower H-atom energies, however, where these $ns \rightarrow 2p$ emissions become increasingly smaller fractions of the total emissions, their uncertainties are substantially larger.

Figures 2(a) and 2(b) show the polarizations of the H_α and H_β radiations, respectively, from the collisions.[8] The uncertainties here are typically about ± 0.03 for H-atom energies above 0.1 keV, but increase to about twice this value at the lowest H-atom energies.

Some remarkable similarities exist between the $3s \rightarrow 2p$ emission cross sections shown in Fig. 1(a) and those for the

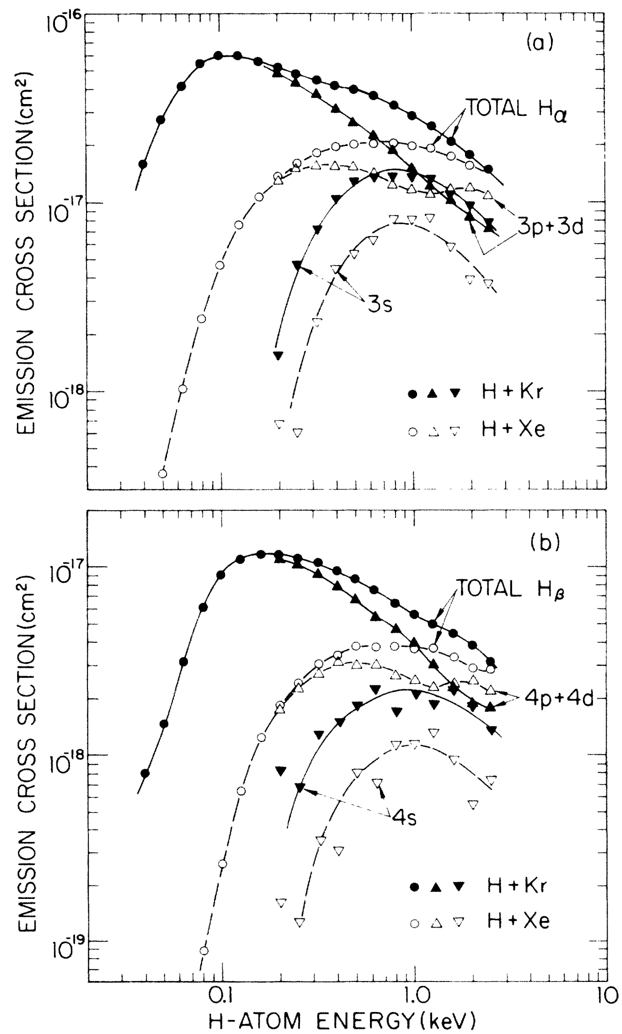

FIG. 1. H_α and H_β emission cross sections for H+Kr and H+Xe collisions.

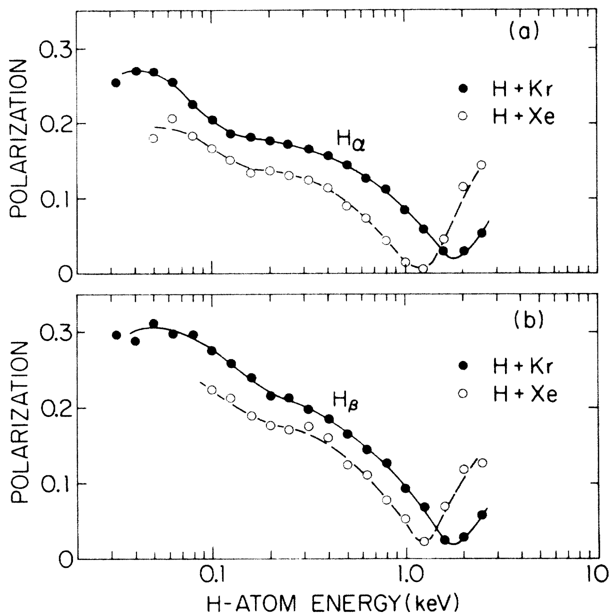

FIG. 2. Polarization of H_α and H_β radiations from H + Kr and H + Xe collisions.

other rare-gas-atom targets reported earlier.[1,3,4] For all reactions, the $3s \rightarrow 2p$ emission cross sections always reach their maximum values for H-atom energies near 1 keV. In addition, the magnitudes of all these cross sections at their maxima are surprisingly similar (ranging from 1.9×10^{-17} cm^2 for Ar targets to 0.5×10^{-17} cm^2 for He targets). Comparisons of the $4s \rightarrow 2p$ emission cross sections presented in Fig. 2(b) with the data for the other targets also show comparable similarities. In fact, the 4s to 3s excitation cross-section ratio[9] as a function of H-atom energy is the same (to within data scatter) for all targets.[4]

In the low range of the H-atom energies covered in these experiments (the collision velocity being well below the Bohr velocity), it was expected that the mechanisms that lead to population of all reaction-product states would be highly dependent on the details of the transient molecules existing during the interactions. However, for the case of populating these excited *ns* states, this does not appear to be true. Indeed, the internal structures of the targets in these interactions seem to play a rather inert role in these excitation processes.

In sharp contrast, the $(np \rightarrow 2s)+(nd \rightarrow 2p)$ emission cross sections such as those shown in Fig. 1 for Kr and Xe targets generally exhibit large differences from one target to another (the exception being Ar and Kr targets, as discussed below). Because most of these emissions come from $nd \rightarrow 2p$ transitions,[5] the interactions leading to population of these excited *nd* states do depend strongly on the internal structures of the targets involved and thus on the transient molecules governing the interaction details.

As noted above, the data shown in Fig. 1 for Kr targets are very similar to those reported earlier for Ar targets,[1] which also exhibit large cross-section maxima for *nd*-state populations in the 0.1-keV H-atom energy range. For all other targets, however, the specific interactions that lead to these large 3*d*-state populations at very low H-atom energies are either not operative (as seems to be the case for Xe targets) or much less effective (for He and Ne targets, where the emission cross sections exhibit similar but much smaller structures, presumably also from *nd*-state excitations).[4]

For the case of H + Ar collisions, it was suggested earlier[1] that the reaction sequence $H+Ar \rightarrow H^- + Ar^+ \rightarrow H^* + Ar$ might be responsible for the large *nd*-state-excitation probability at low H-atom energies. Here, transient Coulomb states, populated early in the interaction, would (diabatically) cross and feed the product H^* states on the outward leg of the collision at large internuclear separations. Because H^- and Ar^+ have ^1S and ^2P electronic configurations, respectively, the Coulomb states can be only $^2\Sigma$ or $^2\Pi$ in character. At large receding separations (where the molecular and H-atom-beam axes again become synonymous), these molecular states would reduce to the $m_l=0$ and ±1 sublevels of the *nd* states, but the $m_l=\pm2$ sublevels could not be populated (assuming the product Ar atom was in its ground ^1S configuration). This would explain the large positive polarizations of the H_α and H_β radiations observed at low H-atom energies,[10] as well as other features of these data.[1]

The same mechanism could occur for the H + Kr reaction studied here. However, for He and Ne targets, the high ionization potentials of these atoms cause such Coulomb states to lie well above the H^*+He and H^*+Ne product states, preventing any comparable state crossings on the outward legs of these interactions. Thus, the absence of large *nd*-state-excitation cross sections at low H-atom energies for these reactions is consistent with the above explanation of such excitation processes for Ar and Kr targets.

Further support for this model is provided by the data for Xe targets shown in Fig. 1, which also do not exhibit large *nd*-state-excitation maxima at low H-atom energies. Here, however, because of the low ionization potential of Xe, the lowest H^-+Xe^+ state lies below the energy of the product H^*+Xe states of interest, also preventing this Coulomb state from serving as an efficient collision intermediary for the reaction.[11] While not proving the correctness of the intermediate-Coulomb-state model for Ar and Kr targets, these data for Xe targets are at least consistent with this hypothesis.

Even though the cross-section data shown in Fig. 1 for Kr and Xe targets at low H-atom energies are quite different, the polarization data shown in Fig. 2 exhibit considerable similarity. Although the H_α and H_β polarizations are somewhat smaller for H impact on Xe than on Kr at low H-atom energies, the most striking features of these results are that the data for the two targets can be essentially superimposed with a small relative shift of the H-atom-energy scale, and the existence of the sharp minima in the polarizations at H-atom energies near 1.2 and 1.7 keV for Xe and Kr targets, respectively. (There may also be a minimum in the H_α polarization for H + Ar collisions[1] at or slightly above 2 keV, although the data uncertainties prevent a definitive conclusion. However, such a minimum would be required to join these polarization data with the positive values reported by Hughes, Petefish, and Kisner[12] at higher H-atom energies.)

The existence of these polarization minima implies that the $m_l=0$ and ±1 substates of the *nd* states are less dominantly populated[10] than at nearby H-atom energies. For H + Xe collisions, at least, this appears to be consistent with small minima in the $(np \rightarrow 2s)+(nd \rightarrow 2p)$ emission cross sections for an H-atom energy near 1.2 keV as indicated in Fig. 1. While this correlation is pleasing, it provides little insight into the specific reason(s) for this competition between these m_l-substate populations, or why it should occur in this specific range of H-atom energies. Unfortunately, the details of such interactions remain insufficiently known at this time to allow precise identification of the physical phenomena observed.

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[3]B. Van Zyl, M. W. Gealy, and H. Neumann, Phys. Rev. A **28**, 176 (1983).

[4]B. Van Zyl, M. W. Gealy, and H. Neumann, Phys. Rev. A **31**, 2922 (1985).

[5]Although the emission components from the $np \rightarrow 2s$ and $nd \rightarrow 2p$ transitions could not be separated experimentally, most of these emissions probably come from $nd \rightarrow 2p$ transitions because of the small branching ratio (~ 0.12) for $np \rightarrow 2s$ decay.

[6]B. Van Zyl, N. G. Utterback, and R. C. Amme, Rev. Sci. Instrum. **47**, 814 (1976).

[7]B. Van Zyl, G. H. Dunn, G. Chamberlain, and D. W. O. Heddle, Phys. Rev. A **22**, 1916 (1980).

[8]These data are total-emission polarizations. Because the emissions from excited ns states are not polarized, the $(np \rightarrow 2s) + (nd \rightarrow 2p)$ emissions must be more polarized than the data shown.

[9]Because cascade population of these ns states from higher-lying np states should be small (these np states decaying preferentially to the $1s$ and $2s$ states), the $ns \rightarrow 2p$ emission cross sections can be used together with the appropriate branching ratios to determine the ns-state-excitation cross sections. The nd-state-excitation cross sections can be similarly determined, although as discussed in Ref. 1, the degree of cascade from higher-lying nf states has not been determined accurately. The $3s \rightarrow 2p$ and $3d \rightarrow 2p$ transitions have branching ratios of unity, while the $4s \rightarrow 2p$ and $4d \rightarrow 2p$ branching ratios are 0.584 and 0.746, respectively.

[10]U. Fano and J. H. Macek, Rev. Mod. Phys. **45**, 553 (1973). According to expressions presented in this paper, the polarizations of the radiations from the $m_l = 0$, ± 1, and ± 2 substates of nd states should be $+0.48$, $+0.26$, and -0.70, respectively.

[11]This is true only for the lowest $^2P_{3/2}$ state of the Xe^+ ion, but not for the $^2P_{1/2}$ state because of the large doublet spliting (~ 1.3 eV) present in this ground electronic configuration. However, this may suggest that the $^2P_{3/2}$ states for Ar^+ and Kr^+ ions as well may be the ones most effective in the molecular Coulomb-state interaction channel.

[12]R. H. Hughes, H. M. Petefish, and H. Kisner, Phys. Rev. A **5**, 2103 (1972).