Measurement of electron-transfer cross sections for H(3l) in intermediate-energy H^+-He collisions

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Cross sections have been measured for the production of H(3l) atoms via electron transfer in proton-helium collisions from 25 to 100 keV. In the experiment, the intensity of Balmer-α radiation is measured as a function of proton energy. These measurements are combined with previously measured density matrices for the same collision to produce relative cross sections. Our relative electron-transfer results, accurate to 3–7 %, are normalized to the absolute σ_{3s} cross-section measurements of Brower and Pipkin [Phys. Rev. A **39**, 3323 (1989)] at 60 keV. Comparison of our σ_{3l} cross-section measurements with other experimental measurements shows general agreement to within 20%, with larger differences for older results. The recent calculation of Shingal and Lin [J. Phys. B (to be published)] agrees to within 13% of our measurements of σ_{3s} above 30 keV, but predicts a low-energy oscillatory behavior of σ_{3p} and σ_{3d} not present in experimental results.

In ion-atom collisions, electron transfer dominates the intermediate-energy regime, where the ion velocity nearly matches the orbital-electron velocity of the target atom. For this reason, electron-transfer cross sections have been measured in simple collisions for many years.[1–6] Previously, we determined density matrices describing H($n=3$) atoms formed in proton-helium collisions.[7,8] Our results were normalized to σ_{3s} at each energy. We have now measured σ_{3s} as a function of energy and can normalize our previous results to bring them onto an absolute scale. We compare our results to four experimental measurements and three theoretical calculations.

The apparatus was described previously.[7] A proton beam traverses a He gas cell in which there is an applied electric field. Balmer-α radiation is observed perpendicular to the beam from a section of the gas cell. The proton current varies with proton energy from 0.5 μA at 25 keV to 3 μA at 100 keV. The He gas pressure is 1 mTorr. A transverse electric field of 390 V/cm is directed perpendicular to both the proton beam and the direction of observation. At this field strength significant Stark mixing of the $n=3$ manifold produces a shorter effective lifetime for H(3s) atoms, leading to a larger counting rate. Additional measurements using zero electric field, which have a larger uncertainty, agree with the 390-V/cm results.

The intensity of light polarized parallel to the beam $I_\parallel$ is measured as a function of proton energy. Each density-matrix element contributes to $I_\parallel$:

$$I_\parallel=\sigma_{3s}\sum_{\substack{l,m\\l'm'}}\rho_{3lm;3l'm'}\left[f^{(t)}_{0;lm;l'm'}+f^{(t)}_{1;lm;l'm'}+\frac{\sigma_{4s}}{\sigma_{3s}}\left(g^{(t)}_{0;lm;l'm'}+g^{(t)}_{1;lm;l'm'}\right)\right]. \tag{1}$$

The density-matrix elements $\rho_{3lm;3l'm'}$, relative to σ_{3s}, were measured previously.[8] The fitting functions $f^{(t)}_{ijk}$ and $g^{(t)}_{ijk}$ for the ith Stokes parameter for a transverse electric field for individual H($n=3$) and H($n=4$) density-matrix elements were numerically calculated.[7] The σ_{4s}/σ_{3s} ratio is determined from theoretical calculations.[9] By measuring $I_\parallel$ and calculating the sum in Eq. (1) we determine σ_{3s} as a function of proton energy. The relative σ_{3s} are normalized at 60 keV to the result of Brower and Pipkin,[6] since the absolute detection efficiency of our optical

TABLE I. Electron-transfer cross sections σ_{3l} for proton-helium collisions.

Proton energy (keV)	σ_{3s} (10^{-18} cm^2)	σ_{3p} (10^{-18} cm^2)	σ_{3d} (10^{-18} cm^2)
25	0.686±0.022	1.209±0.042	0.2250±0.0081
30	1.215±0.039	1.194±0.042	0.1782±0.0070
35	1.652±0.049	1.118±0.037	0.1525±0.0058
40	1.951±0.054	0.944±0.029	0.1327±0.0049
50	2.141±0.065	0.659±0.024	0.1053±0.0047
60	2.000[a]±0.066	0.453±0.020	0.0838±0.0044
80	1.417±0.057	0.247±0.015	0.0507±0.0037
100	0.910±0.036	0.1453±0.0089	0.0300±0.0021

[a]Normalization value from Ref. 6.

system is unknown. We believe this absolute normalization is correct because of the general agreement at higher energies for σ_{3s} among our results, three other experimental measurements,[3,5,6] and one theoretical calculation,[10,11] in particular, the close agreement between Lenormand[5] and Brower and Pipkin[6] at 60 keV. Our relative cross-section measurements are put on an absolute scale using the normalized values of σ_{3s}.

Table I lists the absolute electron-transfer cross sections σ_{3l}. The relative uncertainties are (i) 0.3–0.7 % from $I_{\parallel}$, (ii) 2–3.5 % from previously determined density-matrix elements,[8] and (iii) 2% from the current measurement caused by an uncertainty in the amount of beam neutralization due to electron transfer. The results are repeatable within the total relative uncertainty of 3–7 %. The uncertainty in the absolute normalization is 20%.[6] The results shown in Table I include corrections for cascade from H($n=4$) which influence the 25-keV results by 5% and the 100-keV results by 1%.

Figures 1–3 compare our results to four experimental measurements[1,3,5,6] and three theoretical calculations.[10–13] Three experimental groups have used the exponential decay method: Hughes *et al.*,[1] Ford and Thomas,[3] and Lenormand.[5] The intensity of Balmer-α radiation is measured as a function of position following a gas cell. The signal is deconvoluted into three exponential curves characteristic of decay from 3*s*, 3*p*, and 3*d* states. No correction is made for cascade. Another experimental method is the microwave resonance optical detection technique of Brower and Pipkin.[6] A detector is placed downstream from a microwave cavity and a gas cell. Microwave radiation drives transitions within the $n=3$ manifold and Balmer-α intensity is measured as the microwaves are turned on and off. Corrections are made for cascade from H($n>3$) atoms up to $n=8$. Systematic effects in these experiments have been discussed previously.[2,14] The uncertainty in the absolute value for all of the experiments is reported to be about 20%. Three calculations have been performed for this collision. Jain, Lin, and Fritsch[12] use the augmented atomic orbital (AO+) method, a modified two-center atomic-orbital expansion

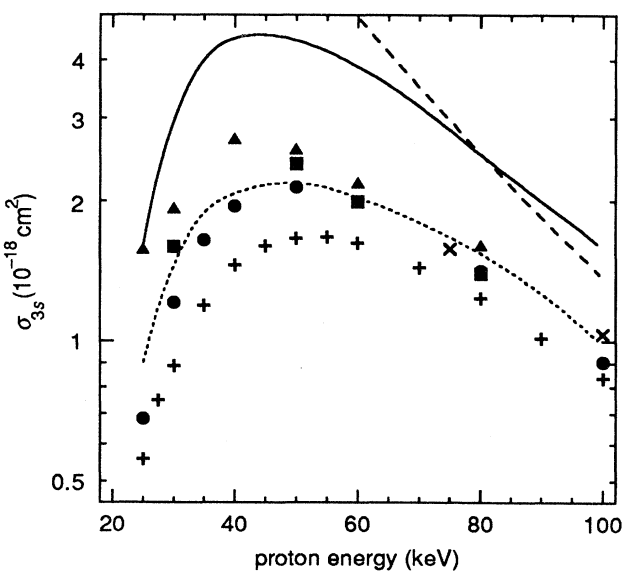

FIG. 1. σ_{3s} as a function of proton energy. ●, present results; ■, Brower and Pipkin (Ref. 6); ▲, Lenormand (Ref. 5); ×, Ford and Thomas, (Ref. 3); +, Hughes *et al.* (Ref. 1); ——, Jain, Lin, and Fritsch (Ref. 12); · · · ·, Shingal and Lin (Ref. 10); — — — (Ref. 13).

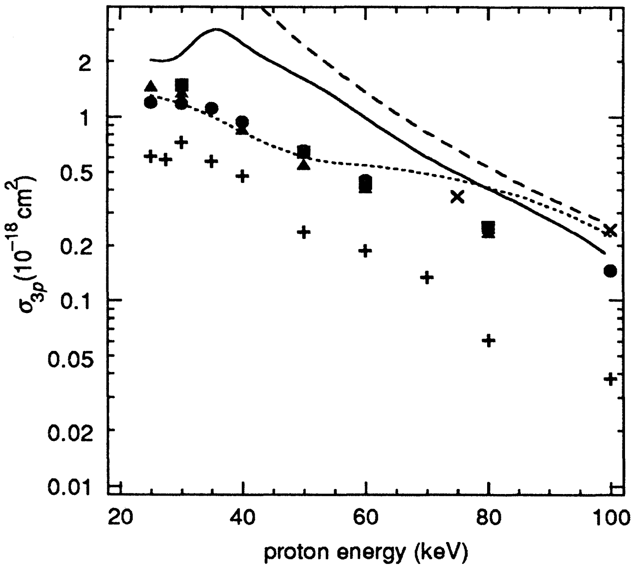

FIG. 2. σ_{3p} as a function of proton energy. Same symbols as Fig. 1.

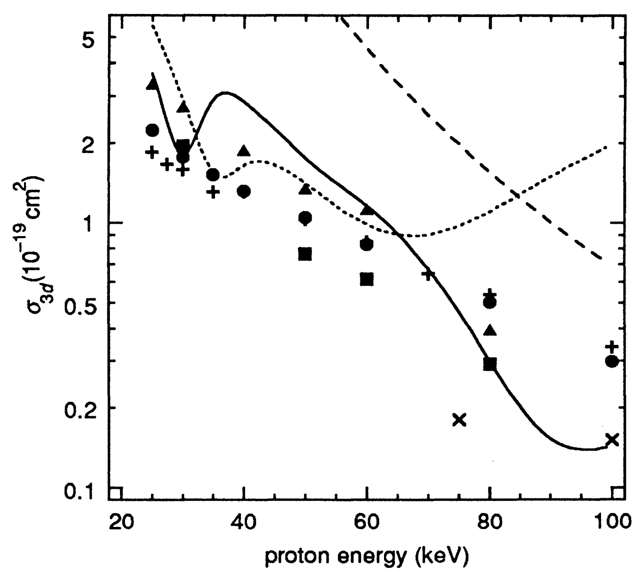

FIG. 3. σ_{3d} as a function of proton energy. Same symbols as Fig. 1.

supplemented by pseudostates. Shingal and Lin[10,11] use the same method with a much larger set of basis states. The calculations by Dubé[13] use the continuum distorted-wave approximation with postcollision interaction[15] (CDW-PCI).

For σ_{3s} above a proton energy of 45 keV all of the experimental results agree to within 18%, except for Hughes *et al.*[1] For σ_{3p}, Lenormand,[5] Brower and Pipkin,[6] and the present results agree to within 23% at all energies. For σ_{3d} below 80 keV, our results agree to within 41% of both Lenormand[5] and Brower and Pipkin,[6] although their results differ by as much as 57%.

The CDW-PCI theory is a high-energy approximation. As the collision energy decreases, the predicted cross sections increase monotonically, overestimating σ_{3l} by a factor of 10 to 15 at 25 keV. At 100 keV, the calculations asymptotically approach the experimental measurements. For all σ_{3l}, CDW-PCI predicts smooth variations as a function of energy.

The calculations of Jain, Lin, and Fritsch[12] overestimate σ_{3s} by a factor of 2. The recent calculations by Shingal and Lin[10,11] agree to within 13% of our measurements of σ_{3s} above 30 keV. Both coupled-state calculations predict oscillatory behavior for σ_{3p} and σ_{3d} not found in experimental measurements. Because the cross sections σ_{3l} are several orders of magnitude smaller than the $H(n=1)$ cross section, coupled-state calculations must include large basis sets to be accurate.

In our previous research, considerable effort was made to eliminate systematic effects in the experiment, leading to self-consistent results.[7] Because of this we believe our relative results for σ_{3l} are the most accurate to date, and should therefore be used in comparison with future experimental and theoretical research.

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