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## Publication Date

1980-11-01

LBL-11732 c.2
Preprint

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

Accelerator & Fusion
Research Division

To be submitted to Physical Review A

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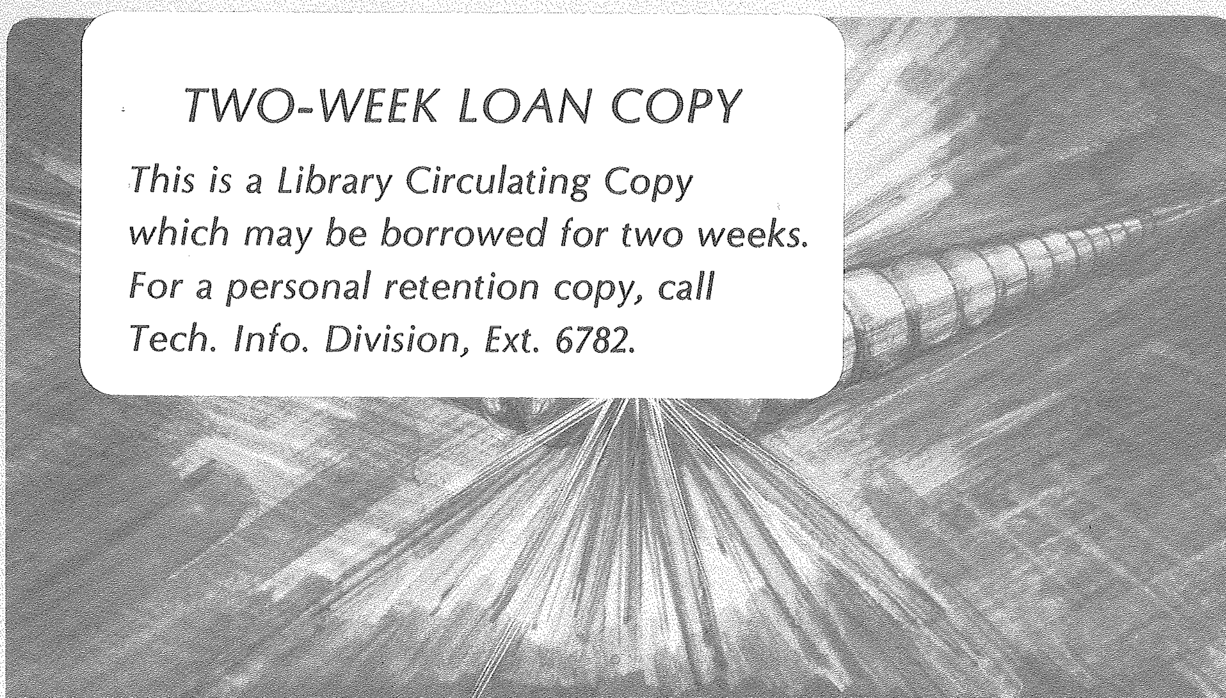
November 1980









Prepared for the U.S. Department of Energy under Contract W-7405-ENG-48

## DISCLAIMER

LBL-11732

To be submitted to Physical Review A:
Comments and Addenda

# Collisions of Fast, Highly Stripped Carbon, Niobium, and Lead Ions with Molecular Hydrogen

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The range of experimental confirmation of our scaling rule for electron loss from a hydrogen atom in collision with a heavy, highly stripped ion has been considerably broadened by new measurements for carbon, niobium, and lead ions in molecular hydrogen.

PACS numbers: 34.70.+e, 34.50.Hc

November 6, 1980

In 1978 we reported a scaling rule[1] for the energy and charge-state dependence of electron loss from a hydrogen atom in collision with a fast, highly charged projectile ion, where electron loss is the sum of charge transfer and ionization. This scaling rule was based on CTMC (classical-trajectory Monte-Carlo) calculations[2,3] for projectile energies from 50 keV/amu to 5 MeV/amu, and for projectile charge states from 1 to 50. We found that the electron-loss cross sections reduced to a single curve when cross section divided by charge state, $\sigma/q$, was plotted as a function of energy per nucleon divided by charge state, $E/q$.

Experimental confirmation of the scaling rule was based on measurements in an $H_2$ target with $Fe^{+q}$ projectiles in the energy range 103 to 1160 keV/amu, with q in the range +3 to +22 and E/q in the range of 10 to 100 keV/amu÷q. In this paper we present new measurements of electron loss from $H_2$ for collisions with projectiles which considerably extend the charge state, energy, and E/q range of our previous measurements. The results indicate that the electron-loss cross section is essentially independent of the chemical species of the highly stripped projectile. New measurements were performed with: $C^{+q}$ projectiles, q=+4 to +6, at energies of 0.3, 1.1, and 4.7 Mev/amu; $Nb^{+q}$, q=+23 to +36 at 3.4 MeV/amu; and $Pb^{+q}$, with q=+52 to +59 at 4.7 MeV/amu.

The experimental method we used has been previously described[3-5] and will be stated only briefly here. A fast ion beam from the Berkeley SuperHILAC was stripped in a thin C foil, giving rise to ions in high charge states; a single charge-state beam was then selected by magnetic analysis. After suitable collimation the beam passed through the target cell. Slow ions and electrons produced in the target gas by passage of fast projectiles were swept by a transverse electric field and collected on parallel collector plates. Projectile ions were charge-state analyzed in a second magnet located downbeam from the target, and ions in either the initial charge state or those having captured (or lost) an electron in the target were detected using a double Faraday-cup assembly or an array of solid-state detectors. Charge-state fractions were measured as a function of target thickness, allowing a determination of the cross sections for target ionization and electron capture and loss by the beam in $H_2$. Corrections for second-order processes[4] were also made.

Our results[6] for electron loss are shown in Table I. The sources of the uncertainties shown are discussed in Refs. 4 and 5. For purposes of comparison[1] with H-target calculations, we divide our $H_2$ results by 2, which introduces an uncertainty of $\pm 25\%$. The present results (and previous measurements with iron projectiles) are shown in Fig. 1, along with our previously determined scaling rule[1] based on the CTMC calculations.

We see that the present measurements are in quite good agreement with the theoretical cross sections, taking into account the 25% uncertainty[1] in the calculated cross sections, the 10% minimum uncertainty in the experimental cross sections, and the 25% uncertainty introduced for the comparison of H and $H_2$ targets. This agreement extends experimental confirmation of our scaling rule for electron loss in hydrogen to charge states as high as +59 and to E/q values in the range 10–300 keV/amu ÷ q. These results are consistent with the electron-loss cross section divided by charge state being a function only of E/q, and hence not dependent on the chemical species of the projectile. The measured value for the 4.7 meV/amu $C^{+6}$ cross section deviates from the good agreement with theory. Measurements with this same projectile in rare-gas targets[5] were similarly larger than theory. Further measurements would be required to verify this apparently anomalous effect.

We would like to thank Dr. R.E. Olson for helpful discussions of the calculations and experiments, and Dr. P. J. Schneider and K. R. Stalder for assistance with the experiment.

This work was supported by the Fusion Energy Division of the U.S. Department of Energy under contract No. W-7405-ENG-48.

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Table I. Cross section $\sigma_{loss}$ for electron loss from $H_2$ in collision with a fast ion projectile (in units of $10^{-16}$ $cm^2$/molecule).

| Projectile Ion | Energy (MeV/amu) | E/q (keV/amu ÷ q) | $\sigma_{loss}$ | $\sigma_{loss}/2q$ |
|---|---|---|---|---|
| $C^{+4}$ | 0.31 | 77 | $14^{+1.5}_{-2.1}$ | 1.75 |
| $C^{+4}$ | 1.14 | 285 | $5.2^{+0.6}_{-0.8}$ | 0.65 |
| $C^{+5}$ | 0.31 | 62 | $19^{+2.1}_{-2.9}$ | 1.9 |
| $C^{+5}$ | 1.14 | 228 | $7.2^{+0.8}_{-1.1}$ | 0.72 |
| $C^{+6}$ | 0.31 | 51.5 | $25^{+3}_{-4}$ | 2.1 |
| $C^{+6}$ | 1.14 | 190 | $10.0^{+1.1}_{-1.5}$ | 0.84 |
| $C^{+6}$ | 4.75 | 790 | $4.8^{+0.5}_{-0.7}$ | 0.40 |
| $Nb^{+23}$ | 3.6 | 155 | $57.5^{+6.0}_{-8.6}$ | 1.25 |
| $Nb^{+28}$ | 3.43 | 122 | $72^{+8}_{-11}$ | 1.3 |
| $Nb^{+31}$ | 3.43 | 111 | $88^{+10}_{-13}$ | 1.4 |
| $Nb^{+34}$ | 3.43 | 101 | $108^{+12}_{-16}$ | 1.6 |
| $Nb^{+36}$ | 3.43 | 95 | $110^{+12}_{-17}$ | 1.5 |
| $Pb^{+52}$ | 4.65 | 90 | $220^{+24}_{-30}$ | 1.9 |
| $Pb^{+53}$ | 4.65 | 88 | $220^{+24}_{-33}$ | 2.1 |
| $Pb^{+54}$ | 4.65 | 86 | $220^{+24}_{-33}$ | 2.0 |
| $Pb^{+55}$ | 4.65 | 85 | $230^{+25}_{-35}$ | 2.1 |
| $Pb^{+57}$ | 4.65 | 82 | $250^{+28}_{-38}$ | 2.2 |
| $Pb^{+59}$ | 4.65 | 79 | $260^{+30}_{-39}$ | 2.2 |

## Figure Caption

Fig. 1. Hydrogen electron-loss cross section by highly charged heavy ion. Solid line: calculated cross section $\sigma_{loss}$ for electron loss by atomic H in collision with an ion in charge state q; valid for $1 \leq q \leq 50$ and for energies in the range 50 to 5000 keV/amu. Range of E/q values for which curve is valid is indicated by bars shown. Uncertainty in the calculated cross sections is $\pm 25\%$. Dashed line: plane-wave Born-approximation cross section for ionization only (Refs. 7, 8). Closed Symbols: Present experimental results for $C^{+q}$, $Nb^{+q}$, and $Pb^{+q}$ in $H_2$, divided by 2 to allow comparison with the calculations. The uncertainty is 30%. Triangles, 0.31 MeV/amu carbon ions, q = 4-6; squares, 1.1 MeV/amu carbon ions, q=4-6; circle, 4.7 MeV/amu carbon ions, q=6; inverted triangles, 3.4 MeV/amu niobium ions, q = 23-36; star, 4.7 MeV/amu lead ions, q = 52-59. Open symbols: Previous experimental results (Refs. 1 and 2) for $Fe^{+q} + H_2$, divided by a number between 1.5 and 2.0 to allow comparison[1] with the calculations. Squares, 103 keV/amu, q = 7-11; triangle, 110 keV/amu, q = 3; diamond, 282 keV/amu, q = 9; stars, 294 keV/amu, q = 10-15; circles, 1160 keV/amu, q = 11-22.

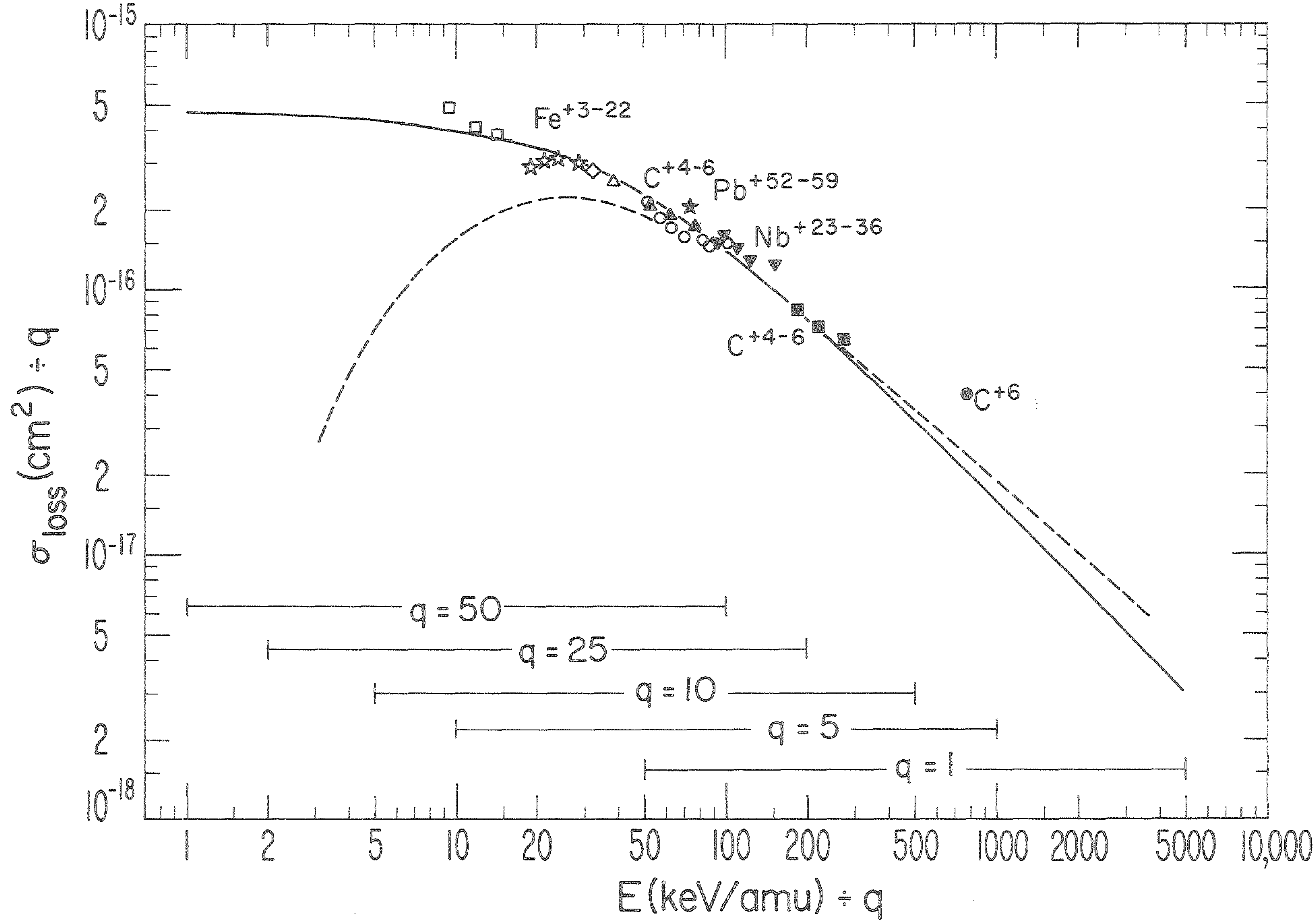


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Fig. 1