Single and double electron loss by fast helium atoms in gases

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Measurements of single and double electron-loss cross sections for He atoms in the gases H_2, He, N_2, Ar, and Kr are reported in the energy range from 0.1 to 4 MeV. The cross sections are determined by the initial-growth method, and the neutral beam is formed by charge transfer neutralization of He^+ in a He gas. The results on single electron loss in H_2 and He targets have been discussed in an earlier paper and compared with theoretical Born-approximation calculations. The present results are compared with those from other experiments and with available theoretical estimates.

I. INTRODUCTION

The present paper is an extension of our earlier work (Horsdal Pedersen and Hvelplund),[1] on electron loss from fast He atoms, in the following referred to as I. Measurements have been performed in the 0.1–4-MeV energy range with H_2, He, N_2, Ar, and Kr as target gases. The single and double electron-loss cross sections σ_{01} and σ_{02} are measured by the initial-growth technique, using a neutral He beam which is predominantly in the ground state when entering the target region.

Most experiments concerned with the measurement of electron-loss cross sections for neutral He (Allison,[2] Barnett and Stier,[3] Fogel *et al.*,[4] Pivovar *et al.*,[5] Solov'ev *et al.*,[6] and Gilbody *et al.*[7]) have been performed at energies below 1 MeV. Apart from I, the only exception is a recent work by Dmitriev *et al.*[8] As discussed in I, where measurements on target gases H_2 and He were reported, high-energy data are important when Born-approximation calculations are to be tested. Theoretical calculations of σ_{01} are at present available for target gases H_2 and He only (Bell *et al.*[9]), but in spite of this, these measurements have been extended to include also the heavier target gases. The purpose of this was to collect high-energy-loss cross sections which might help in the further development of the theory of atomic collisions.

Measurements of σ_{02} in H_2, He, and air have been reported by Allison[10] in the energy range from 0.25 to 0.45 MeV and recently by Dmitriev *et al.*[8] in target gases He, N_2, Ne, and Ar at energies between ~1 and ~8 MeV. The general behavior of σ_{02} in various targets is discussed on the basis of the present experimental results.

When the electron loss from neutral He projectiles is measured, great care should be taken to specify the electronic state of the projectile when it enters the target cell. Gilbody *et al.*[7] have discussed the influence on loss cross sections stemming from admixtures of metastable atoms in the beam. According to these investigations, results found before 1970 may be erroneous owing to unknown metastable fractions in the beam.

II. EXPERIMENTAL APPROACH

The measurements were performed as described in I, and only essential features will be summarized here. Monoenergetic, pure He^+ from a Van de Graaff accelerator (1–4 MeV), or He^+ and He^{++} from the Aarhus 600-keV heavy-ion accelerator (0.1–1 MeV), were partially neutralized when passing through a gas cell containing ~0.1 Torr cm of helium. Electrostatic deflection plates after the neutralizer ensure that only neutral He enters the target cell. Furthermore it was argued in I that these atoms are predominantly in their ground state.

The mixed beam emerging from the 30-cm-long target cell was separated according to charge state in parallel-plate electrostatic analyzer. Finally, the differently charged components were detected by a position-sensitive detector, and the charge-state fractions were easily determined.

At energies above 1 MeV, a solid-state position-sensitive detector was used, as described in I. At lower energies, where the ionization energy available is not high enough to ensure proper position resolution, a special secondary-emission position-sensitive detector was used. This detector has been developed at the Aarhus laboratory for charge-state measurements and has been described by Østgaard Olsen and Hvelplund.[11] Both kinds of detector were used for simultaneous measurements of the intensity of the differently charged beams, thus eliminating effects caused by beam instability.

The cross sections were obtained by means of the formula

$$F_f(\mu) = a_f + \sigma_{0f}\mu + k_f\mu^2 ,$$

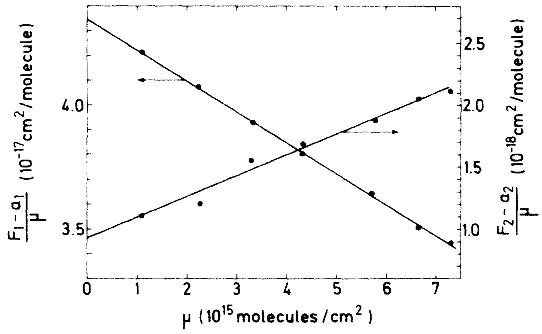

FIG. 1. $[F_f(\mu)-a_f]/\mu$ as a function of μ (cf. text) for 2.5-MeV He in H_2.

where μ is the target thickness, $F_f(\mu)$ is the fraction of ions with charge f, a_f is the fraction formed in the residual gas, and k_f describes the effect of double collisions (for a more detailed treatment, see I). The actual cross sections were found by linear extrapolation of the experimental values of $[F_f(\mu)-a_f]/\mu$ to $\mu=0$. The measurements were performed in the pressure range up to ~10^{-2} Torr, and a typical data curve is shown in Fig. 1.

III. RESULTS

Figures 2–6 show cross sections σ_{01} and σ_{02} versus energy for target gases H_2, He, N_2, Ar, and Kr. The absolute error is estimated to be less than 10% for σ_{01}, while for σ_{02} it varies from ±10% in

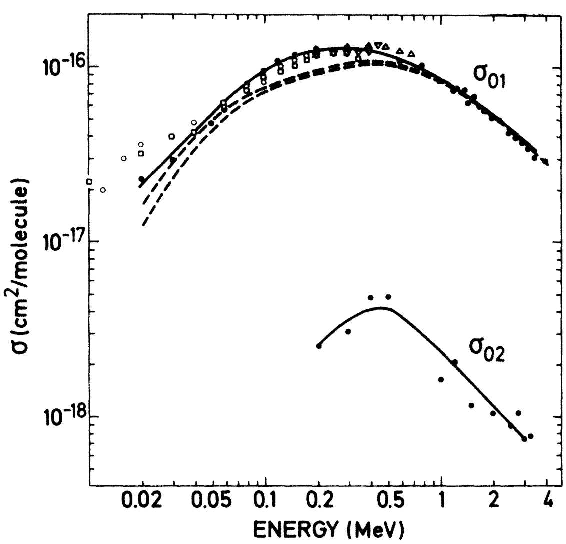

FIG. 2. Energy variation of electron-loss cross sections σ_{01} and σ_{02} for He in H_2: -●-, present results; ▽, Allison (Ref. 2); ○, Barnett and Stier (Ref. 3); △, Pivovar *et al*. (Ref. 5); □, Gilbody *et al*. (Ref. 7); ---, Bell *et al*. (Ref. 9); theory: upper curve is the velocity formulation, lower curve the length formulation.

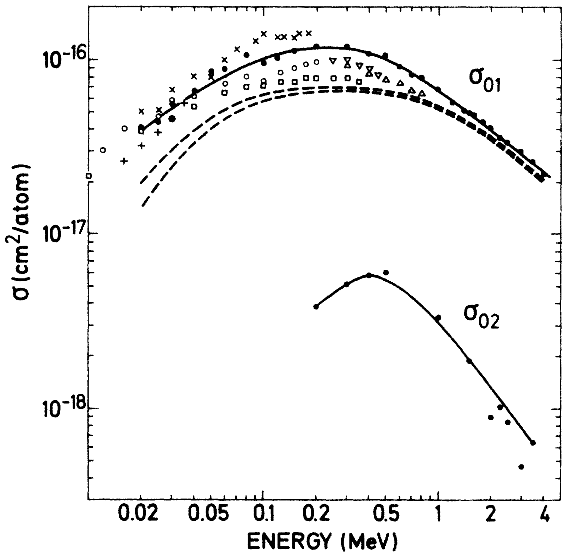

FIG. 3. Energy variation of the electron-loss cross sections σ_{01} and σ_{02} for He in He: -●-, present results; ▽, Allison (Ref. 2); ○, Barnett and Stier (Ref. 3); +, Fogel *et al*. (Ref. 4); △, Pivovar *et al*. (Ref. 5); ×, Solov'ev *et al*. (Ref. 6); □, Gilbody *et al*. (Ref. 7); ---, Bell *et al*. (Ref. 9); theory: upper curve is the velocity formulation, lower curve the length formulation.

target gases N_2, Ar, and Kr to ±20% in H_2 and He.

A variable aperture situated between the target cell and the deflection plates downstream of the beam made it possible to check the influence on the cross section from the loss of beam particles caused by scattering in the target cell. The results of such an investigation are shown in Fig. 7, where the charge-state fractions are plotted as a

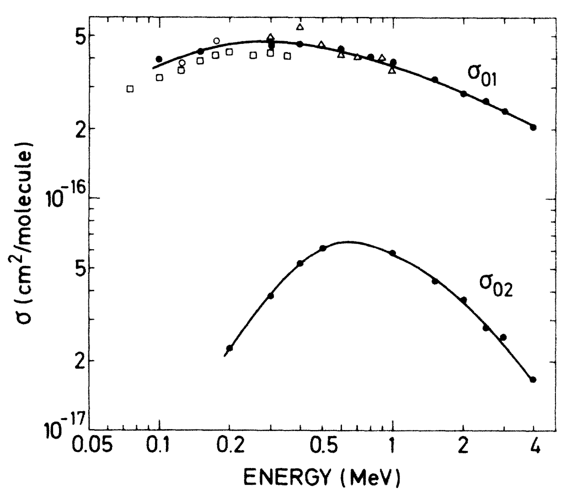

FIG. 4. Energy variation of electron-loss cross sections σ_{01} and σ_{02} for He in N_2: -●-, present results; ○, Barnett and Stier (Ref. 3); △, Pivovar *et al*. (Ref. 5); □, Gilbody *et al*. (Ref. 7).

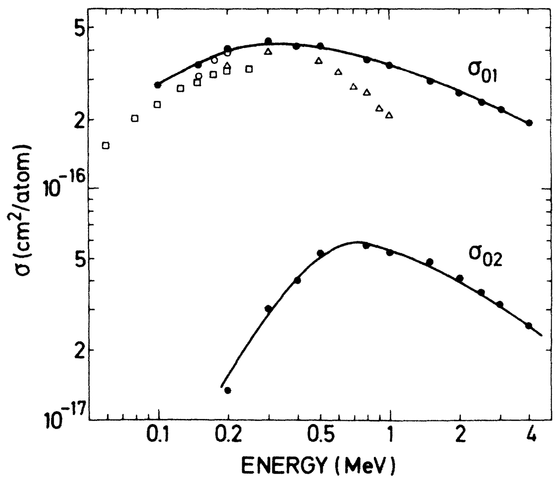

FIG. 5. Energy variation of electron-loss cross sections σ_{01} and σ_{02} for He in Ar: -●-, present results; ○, Barnett and Stier (Ref. 3); △, Pivovar *et al.* (Ref. 5); □, Gilbody *et al.* (Ref. 7).

function of the aperture size at a fixed pressure. It is observed that the charge-state fractions remain constant when the opening of the variable aperture is more than 2×2 mm. At the time of the measurements, the exit hole in the target cell was the limiting aperture, corresponding roughly to a (4×4) mm hole on the scale in Fig. 7. Similar curves were obtained at various energies and pressures and for different target gases. Hence it is believed that all the reported cross sections are total ones.

It was argued in I that the measured cross sections correspond to loss from ground-state atoms. By means of the beam-attenuation technique de-

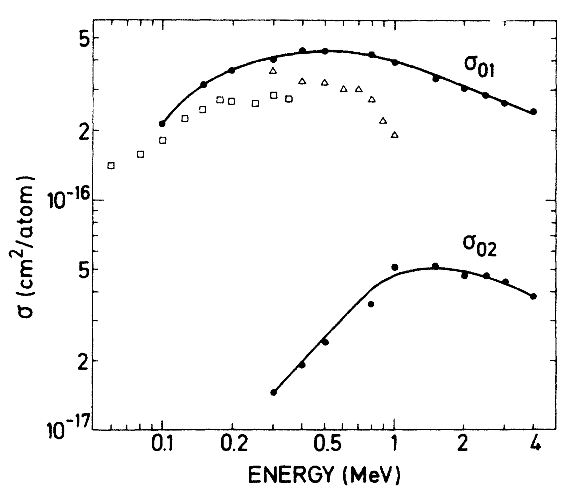

FIG. 6. Energy variation of electron-loss cross sections σ_{01} and σ_{02} for He in Kr: -●-, present results; △, Pivovar *et al.* (Ref. 5); □, Gilbody *et al.* (Ref. 7).

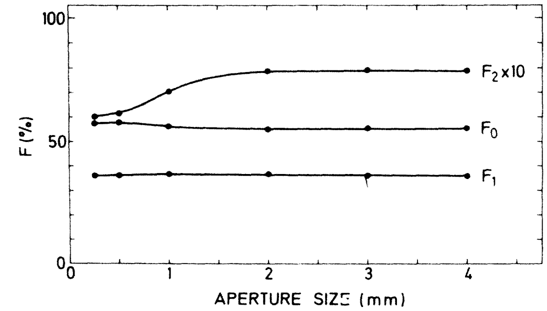

FIG. 7. Charge-state distributions as a function of adjustable aperture size (cf. text) for 1-MeV He through Kr ($\mu = 1.3\times 10^{15}$ atoms/cm^2).

scribed by Gilbody *et al.*,[7] this was proved to hold in the energy range up to 2 MeV.

In a few cases, the charge-state distributions have been measured up to pressures far beyond the single-collision region with the purpose of checking the data-handling procedure. In these cases, the cross sections have been determined by a least-squares fit (Datz *et al.*[12]), where the numerical solutions to the differential equations describing the charge-state variation with target thickness were used. The cross sections thus obtained agreed with those obtained from the low-pressure region, showing that the adapted data-handling procedure does indeed work. The equilibrium charge-state distribution could not be obtained with the present setup because of scattering in the target cell at high pressures. This scattering caused a mixing of the differently charged beams which are only a few mm apart when they hit the detector. Measured variations of the charge-state components F_f for 3-MeV He in H_2 are shown in Fig. 8.

As a by-product of the fitting procedure, the electron-loss cross section σ_{12} was obtained and is given in Table I. The remaining cross sections σ_{10}, σ_{21}, and σ_{20} were found to have little influence when fitting the present data.

In the cases where all the significant cross sections are determined, the charge-state curves can be extrapolated to their equilibrium values by numerical integration of the equations

$$\frac{dF_f}{d\mu} = -\sum_i \sigma_{fi} F_f + \sum_i \sigma_{if} F_i \ ,$$

where i and f can have the values 0, 1, and 2. In Fig. 8 such a charge-state distribution is shown as a function of target thickness for 3-MeV He in H_2. It should be noted that the dominating way of populating the double-charged component, which is by far the most important one at equilibrium at this energy, is via the singly charged one. This gives rise to the nonmonotonic behavior of $F_1(\mu)$,

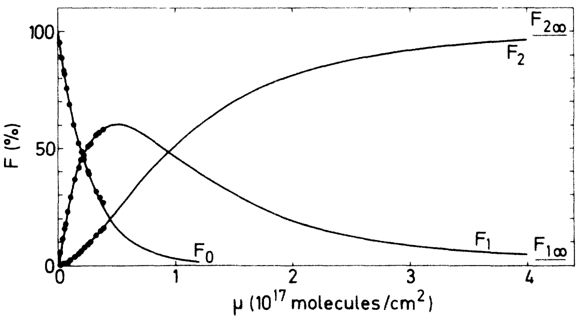

FIG. 8. Charge-state fractions of a 3-MeV He beam as a function of hydrogen-target thickness. The solid lines are computed from the cross sections and the points are experimental values.

showing an increase at small thicknesses until $\simeq 60\%$ of the beam is singly charged and then a decrease toward the equilibrium value of 1.9%. The equilibrium distributions determined as described are also listed in Table I.

IV. DISCUSSION

The single electron loss in collisions with target gases H_2 and He has been discussed in I; hence only a short summary will be given here. In the case of He on H_2 (Fig. 2), all experimental results agree within the quoted experimental error, and excellent agreement is found with the theoretical Born-approximation calculations of Bell *et al.*[9] above ~500 keV. In the He-on-He case (Fig. 3), a larger spread is observed between the results of the various laboratories. Within experimental error, the present result is in agreement with the theoretical curve at high energies (above ~1200 keV), where the Born approximation is expected to be most reliable.

The single electron-loss cross section in the heavier gases is compared with other experimental results in Figs. 4–6. The results of Pivovar *et al.*,[5] i.e., those which are measured at the highest energies, are calculated from the formula $\sigma_{01} = \sigma_{10}\ F_{1\infty}/F_{0\infty}$ and are reported only as an estimate of the single-loss cross section. Nevertheless, good agreement between the two sets of measurements is found in a nitrogen target, whereas for the heavier targets such as Ar and Kr, the two sets of results diverge at higher energies. At 1 MeV, the present values are approximately a factor of 2 larger than those reported by Pivovar *et al.*[5]

The present results may also be compared with those of Gilbody *et al.*[7] for all the target gases used. In the overlap region (100–350 keV), it is observed that the two sets of results agree within experimental error for H_2, N_2, and Ar, the present results being normally some 15% higher. With target gases He and Kr, the two sets of results deviate by as much as 50% at the higher impact energies. This disagreement is hard to understand, particularly since it is argued that both sets of data refer to loss from ground-state He atoms. For comparison, earlier results of Barnett and Stier[3] are shown. In most cases, these agree nicely with the present measurements, but are probably some 20% higher than the ground-state values owing to the presence of long-lived excited states (see Gilbody *et al.*[7]).

In Figs. 2–6 are also shown the experimental values of the double-loss cross section σ_{02}. The only published results with which the present values can be compared, are those of Allison.[10] For H_2 and He targets, Allison reported a value of $0.2 \pm 0.2 \times 10^{-17}$ cm^2 per molecule at 250 keV. The present values at 250 keV are found to be ~0.35 $\times 10^{-17}$ cm^2 per molecule for H_2 and ~0.45×10^{-17} cm^2 per molecule for He.

From the present measurements it is possible to construct the cross section $\sigma_t = \sigma_{01} + 2\sigma_{02}$, a quantity which is directly measurable by means of the condenser method (see e.g., Russek and

TABLE I. Electron-loss cross section σ_{12} and equilibrium charge-state fraction $F_{f\infty}$.

	He in H_2		He in Kr	
	1 MeV	3 MeV	1 MeV	3 MeV
σ_{12} (cm^2/molecule)	1.73×10^{-17} $1.60 \times 10^{-17\,a}$	1.01×10^{-17}	1.31×10^{-16} $1.6 \times 10^{-16\,a}$	1.11×10^{-16}
$F_{0\infty}$(%)	1.3 $(0.4)^a$	0.0	0.6 $(0.6)^a$	0.0
$F_{1\infty}$(%)	18.4 $(22.0)^a$	1.9	24.8 21.4^a	3.3
$F_{2\infty}$(%)	80.3 77.6^a	98.1	74.6 78.0^a	96.7

[a] Results from Ref. 5. Parentheses indicate that the charge-state fraction F_f has not reached equilibrium.

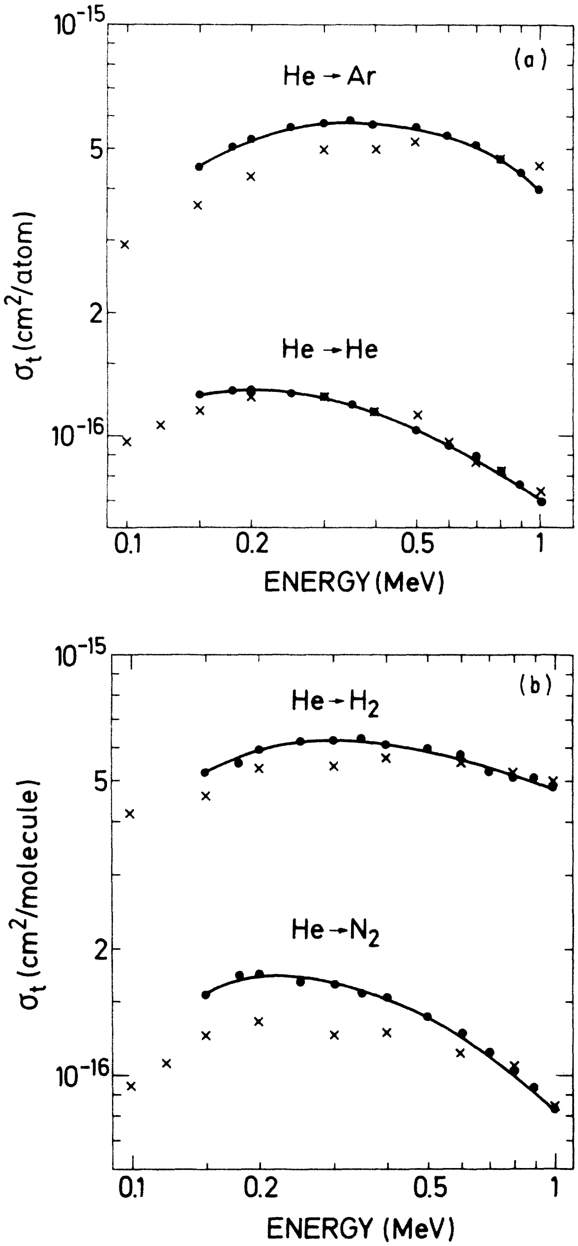

FIG. 9. Energy variation of total-stripping cross section $\sigma_t = \sigma_{01} + 2\sigma_{02}$: ●, present results; × Puckett *et al.* (Ref. 14).

Tawara[13]). Figure 9 shows a comparison of the present values of σ_t with those actually obtained by means of the condenser method of Puckett *et al.*[14] It is noted that the two sets of results agree to almost within experimental error. In particular, it is found that the agreement at high energies is excellent. It should, however, be observed that different energy variations are found in target gases H_2 and Ar. There is no obvious explanation for this discrepancy, especially because Puckett *et al.* also used a "thick" helium neutralizer which, as already mentioned, produces very few long-lived excited He atoms.

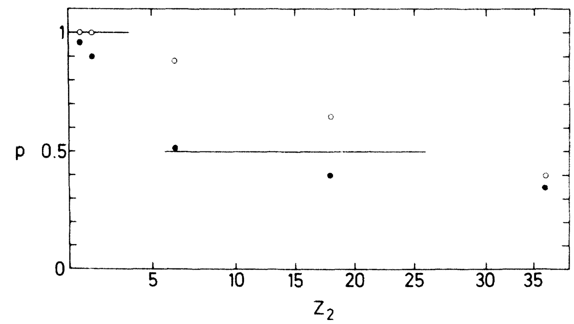

FIG. 10. Exponent p in $\sigma_e \propto v^{-P}$ against target atomic number Z_2: ●, σ_{01}; ○, σ_{02}; —, theoretical values (Bohr, (Ref. 15), cf. text).

Table I shows the present values of σ_{12} and $F_{1\infty}$ at 1 and 3 MeV in H_2 and Kr gases, together with the results of Pivovar *et al.*[5] at 1 MeV. The two sets of data show good agreement, especially when it is born in mind that the values in parentheses are only approximate estimates.

As observed from Figs. 2–6, the cross sections increase at low energies, attain a maximum, and then decrease at higher energies. The maximum value for σ_{01} is found around 300 keV except for Kr, where it is ~500 keV. The similar values for σ_{02} are ~500 and 1500 keV, respectively.

No elaborate theory exists for electron loss from He atoms in the heavier gases. The functional dependence on energy and atomic number of the target at higher energies will therefore be discussed in relation to the qualitative arguments derived by Bohr[15] for electron loss from light projectiles.

In the free-collision approximation, Bohr found for electron loss by fast light particles

$$\sigma_l = 4\pi a_0^2 \, \frac{Z_2^2 + Z_2}{Z_1^2} \left(\frac{v_0}{v}\right)^2$$

for small Z_2,

$$\sigma_l \approx \pi a^2 Z_2^{2/3} Z_1^{-1} \left(\frac{v_0}{v}\right)$$

for intermediate Z_2, and

$$\sigma_l \approx \pi a_0^2$$

for large Z_2, where Z_1 and Z_2 are the atomic number of the projectile and the target, respectively, a_0 is the Bohr radius, v_0 the Bohr velocity, and v is the projectile velocity. The applicability of these formulas in the present energy range has

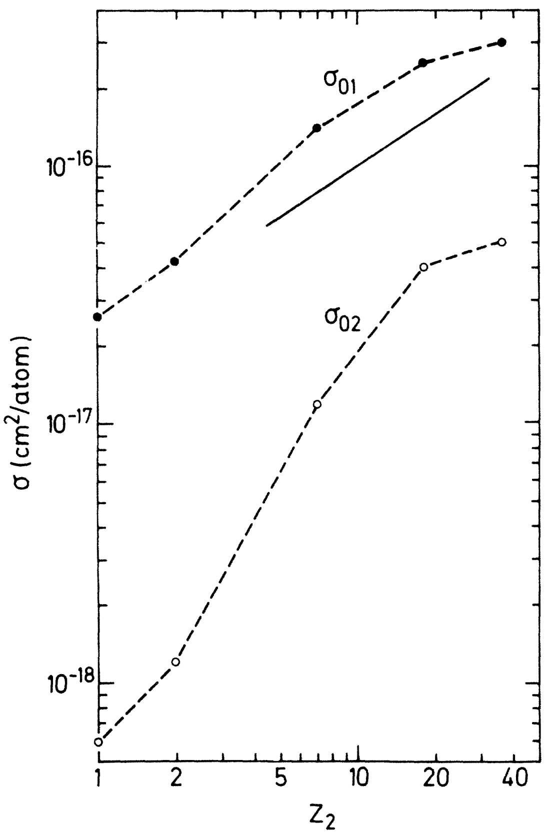

FIG. 11. Electron-loss cross sections at 2 MeV against target atomic number Z_2. The slope of the solid line indicates the $Z_2^{2/3}$ dependence predicted by Bohr (Ref. 15) for intermediate Z_2 values.

been discussed in detail by Nikolaev[16].

For the light targets, σ_l is proportional to v^{-2}, whereas for medium values of Z_2, it is proportional to v^{-1} and finally becomes independent of v for heavy targets.

In order to investigate experimentally this dependence, the power p in the expression $\sigma_l \propto v^{-p}$ was found by fitting a straight line to the high-energy experimental points in Figs. 2–6. Figure 10 shows p as a function of Z_2, and it is observed that the general behavior is as predicted by theory.

It is also predicted by theory that the loss cross section at a fixed velocity should vary as $Z_2^{2/3}$ for intermediate Z_2 values and approach a constant value for large Z_2. This dependence is illustrated in Fig. 11, where σ_{01} and σ_{02} are plotted as functions of Z_2. Strictly speaking, Bohr did not discuss double loss, but as seen from Figs. 10 and 11, the functional dependence of σ_{02} on v and Z_2 is, to some extent, similar to that found for σ_{01}. It should also be noted that the ratio σ_{02}/σ_{01} increases from ~0.02 in H_2 to ~0.16 in the heavy gases. At higher energies, this ratio is found to depend only weakly upon energy, as also reported by Dmitriev *et al.*[8]

Hence it is concluded that the Bohr theory is applicable as far as the main dependence on parameters Z_2 and v is concerned. More precise calculations by Bell *et al.*,[9] who have used the Born approximation, have been shown to be in good agreement with experimental measurements on H_2 and He at high velocities.

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[1]E. Horsdal Pedersen and P. Hvelplund, J. Phys. B 7, 132 (1974).

[2]S. K. Allison, Phys. Rev. 110, 670 (1958).

[3]C. F. Barnett and P. M. Stier, Phys. Rev. 109, 385 (1958).

[4]Ya. M. Fogel, V. A. Ankudinov, and D. V. Philipenko, Zh. Eksp. Teor. Fiz. 38, 26 (1960) [Sov. Phys.—JETP 11, 18 (1960)].

[5]L. I. Pivovar, V. M. Tubaev, and M. T. Novikov, Zh. Eksp. Teor. Fiz. 41, 26 (1961) [Sov. Phys.—JEPT 14, 20 (1962)].

[6]E. S. Solov'ev, R. N. Il'in, V. A. Oparin, and N. V. Fedorenko, Zh. Eksp. Teor. Fiz. 42, 659 (1962) [Sov. Phys.—JETP 15, 459 (1962)].

[7]H. B. Gilbody, K. F. Dunn, R. Browning, and C. J. Latimer, J. Phys. B 3, 1105 (1970).

[8]I. S. Dmitriev, V. S. Nikolaev, Yu. A. Tashaev, Ya. A. Teplova, and Yu. A. Fainberg, in *Abstracts of Papers, Eighth International Conference on the Physics of Electronic and Atomic Collisions, Belgrade, 1973*, edited by B. C. Čobić and M. V. Kurepa (Institute of Physics, Belgrade, 1973), p. 790.

[9]K. L. Bell, V. Dose, and A. E. Kingston, J. Phys. B 2, 831 (1969).

[10]S. K. Allison, Phys. Rev. 109, 76 (1958).

[11]J. Østgaard Olsen and P. Hvelplund, J. Phys. B (to be published).

[12]S. Datz, H. O. Lutz, L. B. Bridwell, C. D. Moak, H. D. Betz, and L. D. Ellsworth, Phys. Rev. A 2, 430 (1970).

[13]A. Russek and H. Tawara, Rev. Mod. Phys. 45, 178 (1973).

[14]L. J. Puckett, G. O. Taylor, and D. W. Martin, Phys. Rev. 178, 271 (1969).

[15]N. Bohr, K. Dan. Vidensk. Selsk. Mat.-Fys. Medd. 18, No. 8 (1948)

[16]V. S. Nikolaev, Usp.Fiz. Nauk 85, 679 (1965) [Sov. Phys.—Usp. 8, 269 (1965)].