Separation of the Screening and Antiscreening Effects in the Electron Loss of He^+ on H_2 and He

E. C. Montenegro and Wilson S. Melo
Departamento di Física, Pontifícia Universidade Católica do Rio de Janeiro, Caixa Postal 38071, Rio de Janeiro, Rio de Janeiro 22453, Brazil

W. E. Meyerhof
Department of Physics, Stanford University, Stanford, California 94305

A. G. de Pinho
Instituto de Física, Universidade de São Paulo, Caixa Postal 20516, São Paulo, São Paulo, Brazil
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The screening and antiscreening contributions to electron loss are separated experimentally through the measurement of the recoil ions and the emergent charge states in the collisions $He^+ + (H_2, He) \rightarrow He^{2+} + (H_2^+, He^+)$. The experimental data are in excellent agreement with calculations which include second-order contributions for the simultaneous ionization of the projectile and the target.

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The role of projectile electrons in target ionization and of target electrons in projectile electron loss, although recognized by Bates and Griffing forty years ago [1], has been ascertained only recently. This role is not only to screen the ionizing nucleus (in which case the electrons attached to that nucleus remain in their ground states during the collision), but also to participate actively in the ionizing process (in which case these electrons are excited or also ionized). For the sake of brevity, these roles have been called "screening" and "antiscreening," respectively [2–5]. Their thorough understanding and experimental separation is important not only in itself, but also for accurate predictions of target x-ray production in particle identification by x-ray emission (PIXE) [6], where antiscreening is usually neglected, or of projectile energy loss, where the change of screening, particularly near the surface of a solid target, can produce unusual effects [7].

These two collision mechanisms have completely different dynamics. While in the screening mode the energy dependence and angular distribution of the electron loss process are determined mainly by the nucleus-electron interaction, the antiscreening mode is better characterized as an electron-electron collision. This fact makes the behavior of the antiscreening channel significantly different from other mechanisms present in ion-atom collisions. The existence of a "threshold" broadened by the momentum distribution of the active target electron [3,4,8] and a broad distribution of the electron loss probability as a function of the impact parameter [5] are peculiar attributes of the antiscreening channel.

In this work, for the first time, we have measured separately the screening and antiscreening contributions to the ionization process (of a projectile). So far, this has been possible only for projectile-electron excitation, where Zouros, Lee, and Richard [8] were able to isolate the antiscreening contribution by choosing a particular transition which requires spin flip, thus discarding the screening mode. Hülskötter *et al.* [9] determined only the total electron cross section, but showed that the screening and antiscreening contributions must both be considered to account for the magnitude of the loss cross section in many different collision systems.

The present experiment consists in measuring the emergent charge states singly and in coincidence with the recoil ions, in collisions of He^+ with H_2 and He targets. The experimental arrangement is basically the same as that described in Ref. [10] and is shown schematically in Fig. 1. Beams of He^+ with 1.5–4.0 MeV energy delivered by the Van de Graaff accelerator of Pontificia Universidade Católica do Rio de Janeiro impinge on a gas cell. The emergent beams (He^+ and He^{2+}) are charge analyzed by a magnetic field and recorded by two surface barrier detectors (D2 and D3). The recoil ions are recorded by a microchannel plate (D1) at the end of a time-of-flight spectrometer housed inside the gas cell. The spectrometer is basically a grid-plate set placed at the center of the gas cell. An 800-V potential established between the grid and the plate accelerates the recoil ions produced by the incident beam and directs the ions through a focusing electrostatic lens placed at the entrance of the time-of-flight tube. In the center of this tube there is a 2-mm aperture to assure proper differential pumping, as well as a sufficiently low pressure for the microchannel plate operation.

Standard fast electronics is used to select recoil ions in coincidence with the He^+ and He^{2+} emergent beams. The overall efficiency of the recoil-ion detection system is determined by measuring the target ionization cross section by 2.0-MeV protons and using the values reported by Rudd *et al.* [11] for normalization. Furthermore, singles (noncoincident) events from the He^{2+} detector are also recorded to obtain the total cross sections for electron loss by the growth rate method [10].

With the above setup the following processes are stud-

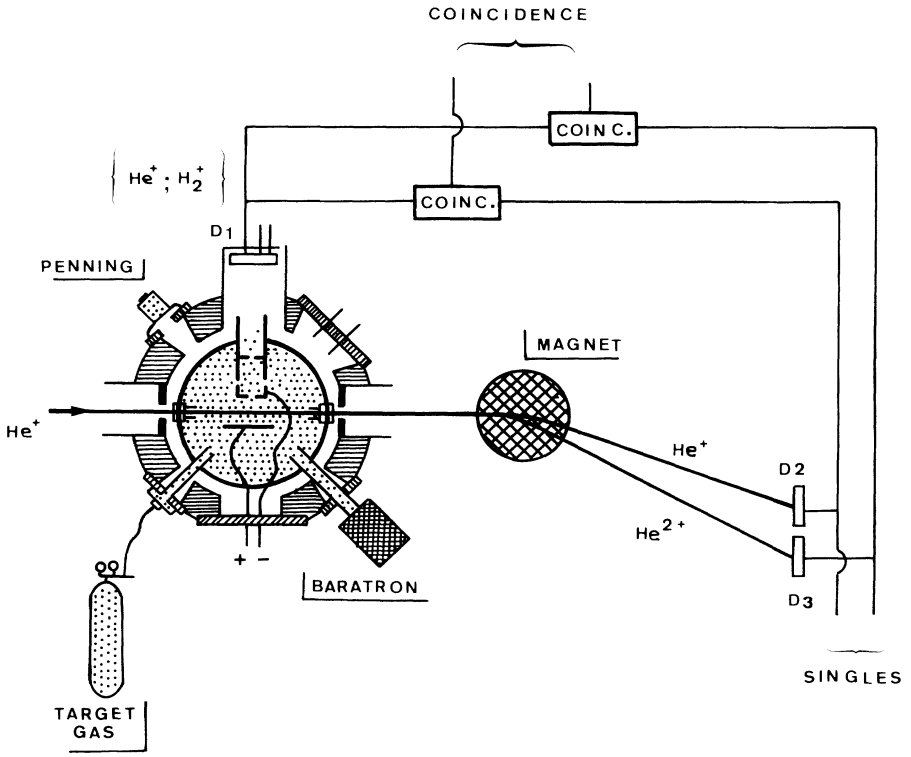

FIG. 1. Sketch of the experimental arrangement. Detector D1 is a microchannel plate and detectors D2 and D3 are surface barrier detectors.

ied:

$$\text{(A)}\quad He^+ + (H_2, He) \rightarrow He^+ + (H_2^+, He^+) + e^- ,$$

$$\text{(B)}\quad He^+ + (H_2, He) \rightarrow He^{2+} + (H_2, He) + e^- ,$$

$$\text{(C)}\quad He^+ + (H_2, He) \rightarrow He^{2+} + (H_2^+, He^+) + 2e^- .$$

Process (A) corresponds to single ionization of the target. Process (B) corresponds to projectile electron loss without target ionization. The main contribution to this process comes from the screening channel. However, the target excitation part of the antiscreening also contributes to this process (above the threshold), but it is only a small fraction of the total cross section for (B). Process (C) corresponds to the ionization part of the antiscreening plus a two-center double ionization. The latter is due to the simultaneous ionization of the projectile and the target electrons by the screened nuclei of the target and the projectile, respectively. Cross sections for processes (A) and (C) are obtained independently by the two coincidence measurements and the sum cross section for (B)+(C) is obtained by an independent measurement of He^{2+} singles. The latter is carried out at five or more different pressures, up to 5 mTorr; all the coincidence data are taken at 1 mTorr. The uncertainties in the singles measurements are determined mainly by the uncertainty in the effective gas cell length and are between 9% and 11%. The uncertainties in the coincidence measurements are mainly due to the uncertainties in the detector efficiency and solid angle, and lie in the (13–15)% range.

Figures 2(a) and 2(b) show the results of the coincidence measurements (C) with H_2 and He targets, respectively. The solid circles give the present data and the open squares are from Ref. [12]. The curves labeled AS are antiscreening calculations of Ref. [4]. These depend on the form factors of the target ground states. For the H_2 target, we used the Stewart molecular form factor of Ref. [13]. For He, the form factor of Salvat *et al.* was used [14], which is based on Hartree-Fock wave functions. If applied to total cross-section data, this procedure agrees within (10–20)% with experiment [9,10].

The curves labeled DI are the two-center double-ionization contributions. This calculation is performed considering double ionization as two independent events, with the cross section given by

$$\sigma_{DI} = 4\pi \int_0^\infty db\, b\, P_{screen}(b) P_{ion}(b) [1 - P_{ion}(b)] , \qquad (1)$$

where $P_{screen}(b)$ is the screening probability of projectile electron loss as given in Ref. [15], and $P_{ion}(b)$ is the target ionization probability calculated following the prescription given in Ref. [10] and neglecting the electron capture channel, which does not contribute significantly in the collision regime studied here [12]. The calculation of the DI process is less accurate than that for the AS process mainly because of the uncertainty in modeling

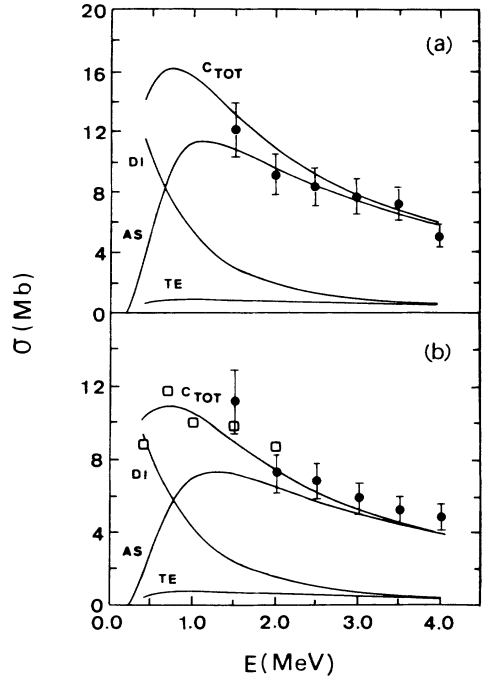

FIG. 2. Cross sections for electron loss (in Mb) of He^+ followed by target ionization in (a) H_2 and (b) He. Theory: AS, antiscreening; TE, target excitation part of antiscreening; DI, double ionization; C_{tot} (=AS−TE+DI), total cross section for process (C). Experiment: solid circles, this work; open squares, Ref. [12].

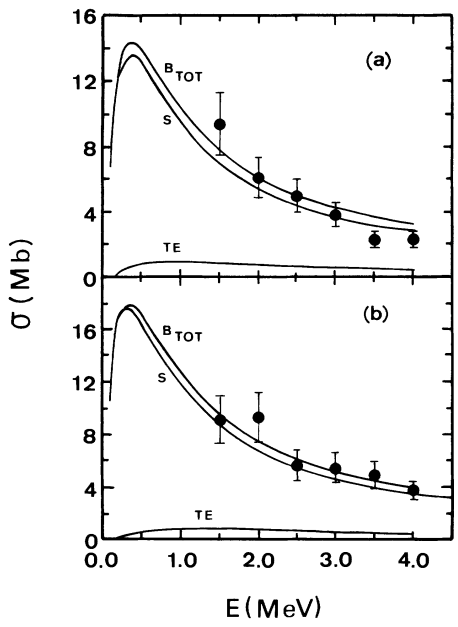

FIG. 3. Cross sections for electron loss (in Mb) of He^+ not followed by target ionization in (a) H_2 and (b) He. Theory: S, screening; TE, excitation part of antiscreening; B_{tot} (=S+TE), total cross section for process (B). Experiment: this work.

$P_{ion}(b)$ for this particular collision regime [10]. The reliability of the procedure was checked by computing the total target ionization cross sections. These agree to within (20–40)% with experiment [16]. The sum of the antiscreening and double ionization contributions is indicated by C_{tot} in Fig. 2.

The AS and DI processes result in the same final target and projectile states and their amplitudes add coherently. However, as shown in Ref. [5], where the semiclassical theory of antiscreening is developed, the antiscreening probability has a much broader impact parameter distribution than the screening probability. Furthermore, the most probable impact parameter for the antiscreening mode is approximately twice that of the screening mode. Since the impact parameter range of DI is determined by that of the screening mode, the overlap with AS is reduced. For this reason, one expects the interference effects between AS and DI amplitudes to be small, which greatly simplifies the calculations because probabilities then can be added incoherently.

The present experimental arrangement determines only the antiscreening cross section accompanied by target ionization, but not by target excitation. On the other hand, the theory of Ref. [4] is based on the closure approximation which includes all accessible target states. Hence, we calculated the loss cross sections accompanied by target excitation (curves labeled TE) and subtracted these from the AS cross sections [17]. As one can see in Fig. 2, the TE contribution is small compared to the others.

Two-center double ionization is a second-order process which is expected to decrease rapidly with increasing projectile energy because $P_{screen}(b)$ and $P_{ion}(b)$ both decrease with energy at higher energies. Our data, and those of Ref. [12], corroborate this behavior and confirm that antiscreening is the dominant mechanism for process (C) at energies above ~2.0 MeV. There is very good agreement with the theory of Ref. [4], which is directly verified for the first time. At lower energies, the uncertainty in the DI calculations prevents any definitive conclusions. Also, in the present measurements, the broad threshold of the antiscreening effect in the region where the translational kinetic energy of the target electron with respect to the projectile frame is insufficient to ionize the projectile electron [4] is masked by the DI mechanism.

Subtraction of the He^{2+} coincidence cross section for process (C) from the cross section for the singles experiment for processes (B)+(C) gives the electron loss cross section not accompanied by target ionization. Theoretically, this process is due to the screening part of electron loss and a contribution from the antiscreening process accompanied by excitation. Figures 3(a) and 3(b) show our experimental results for H_2 and He targets, respectively, together with a screening calculation based on Ref. [4] (labeled by S) and the TE contribution mentioned

above [17]. The sum of these two contributions is indicated by B_{tot} in Fig. 3.

It can be seen from Fig. 3 that the contribution from the TE channel is less than 15% of the total of process (B) over the whole energy range studied. The excellent agreement between theory and experiment gives, for the first time, a clear indication that, when the target is not ionized, electron loss is due essentially to the screened target nucleus with the target electrons remaining in their ground states.

In summary, we have shown that it is possible to separate experimentally the screening and antiscreening contributions to projectile electron loss. We also find that in the collision studied by us, the antiscreening (electron-electron) interaction channel leads mainly to ionization of both collision partners.

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[17] The cross section TE, which is the target excitation part of the antiscreening contribution to electron loss, is obtained from Eq. (1) of Ref. [4]. In evaluating the sum over the principal quantum number n, we have approximated H_2 by two hydrogen atoms and used an independent electron approximation for the first excited states of He, with only singlet states considered. For both targets, the sum is carried out up to $n=4$.