Structure in the Differential Charge-State Fractions of He Following Ionization by Fast Protons

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(Received 9 March 1988)

The differential cross sections for double and single ionization and the corresponding charge-state fractions of He resulting from impact of fast protons have been measured as functions of both the scattering angle (0.25–4.1 mrad) and the impact energy (300–1000 keV) of the proton. The differential cross sections smoothly decrease with the scattering angle, but the fraction of doubly charged ions, F_2, exhibits a distinct peak at ≈ 0.9 mrad. This peak is not easily explained in terms of the single- and double-ionization mechanisms thought to operate at these energies.

PACS numbers: 34.50.Fa, 34.80.Dp

Many-electron processes in atomic collisions have attracted a considerable amount of attention. One goal has been to determine the range of validity of the independent-electron model. The physical cause of deviations from the independent-electron model, commonly as correlation, is the Coulomb interaction between the electrons. Two-electron processes in the collisions of He atoms with fast protons (p) have, in particular, been the subject of extensive research. This system contains the minimum number of particles for a many-electron collision system. Furthermore, the strength of the electron-electron interaction in this system is relatively important because of the low He nuclear charge. Measurements and calculations of total cross sections for both single and double ionization are now available.[1-7]

The single-ionization process is well understood[5] in terms of the first Born approximation. The emphasis has, therefore, been on double ionization, and the data are commonly presented as the ratio of the cross sections for double and single ionization, $R=\sigma^{++}/\sigma^{+}$, or as the charge-state fraction, $F_2=\sigma^{++}/(\sigma^{++}+\sigma^{+})$. The ratio R decreases rapidly with increasing energy at energies below 1 MeV/nucleon,[1,3-5] and reaches an asymptotic value of $\simeq 0.003$ above 10 MeV/nucleon. Double-ionization studies have recently been extended to include ionization by fast antiprotons ($\bar{p}$).[4,5] In a broad range of velocities around 10 a.u., the experimental R values for $\bar{p}$ were found to be almost twice as large as those seen with p impact.

Two theoretical models have been advanced in an attempt to explain first of all this p-$\bar{p}$ difference, but also the energy dependence and magnitude of the individual cross sections. One model focuses on the spatial correlation between the motion of the two electrons of the He atom and explains the observed difference as a result of a charge-state–dependent correlated adjustment of the electronic motion to the presence of the projectile during the collision. For $\bar{p}$, the correlation is such as to increase the strength of the interaction with one electron on the condition that the other electron is being ionized. The effect is reversed for p. Both a quantal calculation[7] and a Monte Carlo calculation[8] based on this effect reproduce part of the observed difference. A simple estimate[9] with an adjustable parameter also agrees reasonably well with the experimental data. The other model explains the charge effect in terms of interference between two different double-ionization mechanisms. One of these, called the two-step-one (TS-1), involves one collision between the projectile and a target electron and a subsequent collision between this recoiling electron and the other electron. The other mechanism, the two-step-two (TS-2), attributes the ionization to consecutive independent collisions of the projectile with each electron. When we use an empirical method to determine the relative phase of the amplitudes, this model also describes the data fairly well.[5]

Previous measurements of F_2, differential in the projectile scattering angle, θ, for simultaneous capture and double ionization of He by p discovered a sharp structure at $\simeq 0.55$ mrad. This structure was explained[10] in terms of the TS-1 mechanism, where one of the electrons is now captured. Therefore, it seemed natural to look for further evidence of this mechanism and possibly other double-ionization mechanisms in the differential cross sections. This Letter describes the measurement of differential cross sections for single, $d\sigma^{+}/d\Omega$, and double, $d\sigma^{++}/d\Omega$, ionization of He by p at energies between 300 and 1000 keV, and θ between 0.25 and 4.1 mrad.

The experimental apparatus has been discussed in detail elsewhere,[10] and will be only briefly discussed here. A beam of protons was collimated and directed through a differentially pumped gas cell. The projectile scattering angle was selected by a solid-state surface-barrier detector, which was screened by annular apertures centered on the beam. The angular resolution given by the apertures varied from 25% for the smallest θ to 10% for the largest. The slow He-recoil ions were extracted electrostatically from the gas cell and the charge states spatially dispersed in a magnetic field. The recoil ion spec-

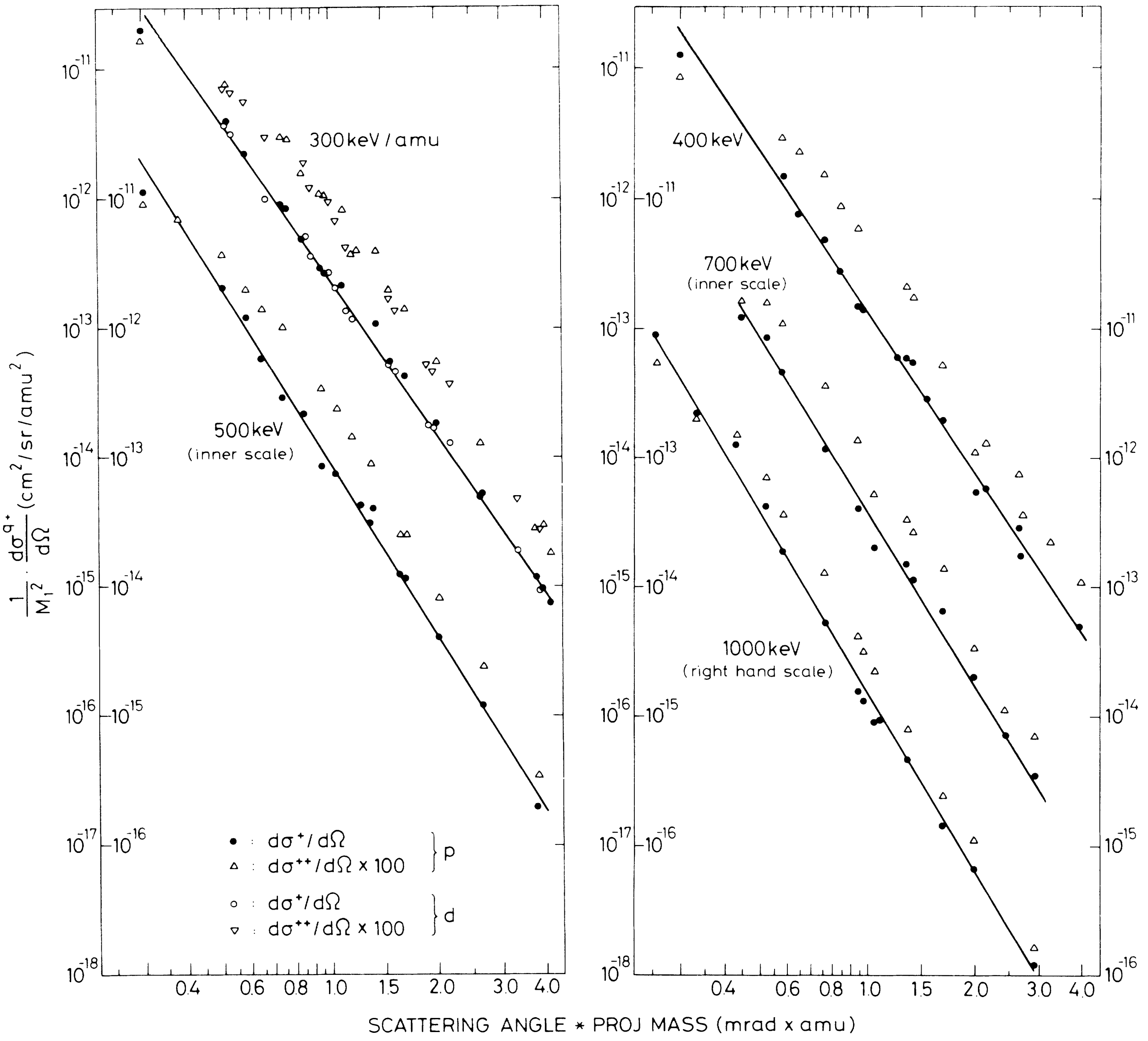

FIG. 1. Differential cross sections for single and double ionization of He by protons ($m=1$) and deuterons ($m=2$). Note the different scales for the different curves and the shift upwards of $d\sigma^{++}/d\Omega$ by 2 orders of magnitude. The curves are drawn to guide the eye.

trum was measured with standard coincidence electronics as a function of the time-of-flight difference and of the dispersion of the recoil ions. This double separation of the charge states greatly improves the reals-to-randoms ratio for the doubly charged ions.

The ratio between the number of coincidences with He^+ (or He^{++}) ions and the number of extracted He^+ ions is equal to $d\sigma^+/d\Omega$ (or $d\sigma^{++}/d\Omega$) divided by the total cross section for formation of He^+. The latter cross section is known[3] and used to extract the absolute differential cross sections shown in Fig. 1. A comparison with the cross section for ionization and simultaneous capture,[10] which is included in the present measurements, shows that this contribution is negligible. Therefore, the cross sections represent simple single- and double-ionization processes. One set of data shown in Fig. 1 (300 keV/nucleon) confirms momentum-transfer scaling,[11] which is expected to apply for the present collisions. Moreover, the figure shows that while the angular dependence of $d\sigma^+/d\Omega$ at each energy is given closely by a simple power law, $d\sigma^{++}/d\Omega$ clearly deviates from this at $\theta < 0.5$ mrad.

Thus, the experimental data suggest a distinction between small and large scattering angles. The limiting

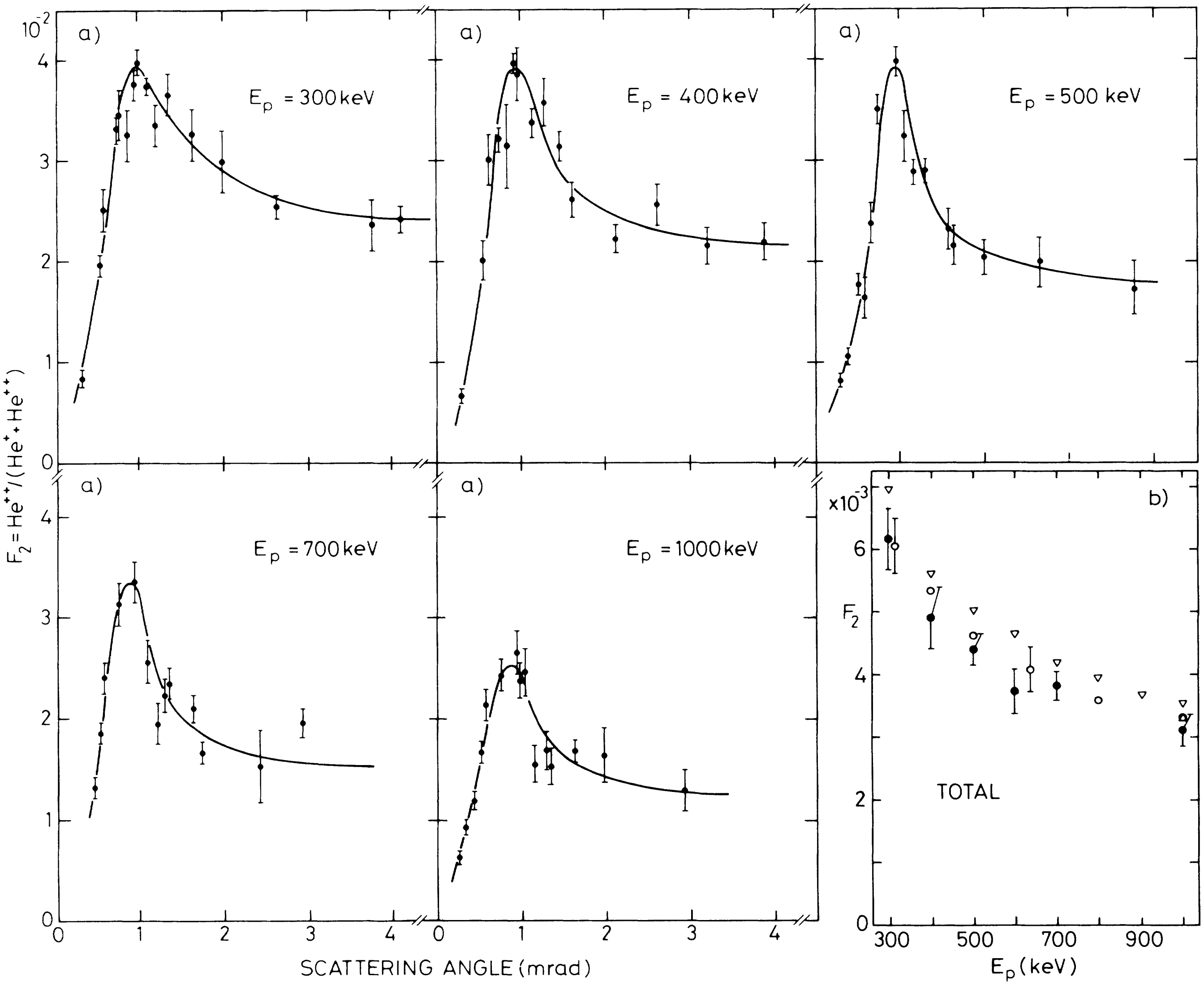

FIG. 2. Charge-state fraction F_2 of He recoil ions from proton-He collisions. (a) F_2 as function of projectile scattering angle at different impact energies. The data are deduced from the cross sections shown in Fig. 1. (b) Total F_2 values obtained from recoil-ion intensities irrespective of projectile scattering angle. Filled circles: present data; open circles: Ref. 4; inverted triangles: Ref. 6. Note the different scales used in (a) and (b). The curves are drawn to guide the eye.

angle is close to the maximum scattering angle $\theta_{\max}$ ($=0.545$ mrad) for a proton off a free electron at rest. The deflection in the large-angle scattering event is, therefore, dominated by the interaction with the target nucleus. We suspect that the behavior at small scattering angles is governed by the interaction with the active electrons. An example of this has previously been seen in electron capture by protons at high velocities, where a peak (the Thomas peak) was predicted in $d\sigma/d\Omega$ at 0.47 mrad, exclusively because of the interaction between the proton and the active electron.[12] The Thomas peak was subsequently observed[13] and the data reproduced by detailed calculations.[14-16] The shape of the Thomas peak is partly given by interference between first and second Born terms.[12] A similar effect may be present here, and the combined scattering off the electrons and the target nucleus in the transition region between small and large deflections may be governed by quantum (diffraction) effects.

A more sensitive comparison of the differential cross sections is obtained from their ratio. The charge-state fractions deduced from these ratios are shown in Fig. 2(a). A distinct peak is observed near 0.9 mrad, accompanied by a strong decrease at smaller θ. We note that the shape of the curves and the location of the peak vary slowly with energy, and point out that the differential F_2 values at each energy are considerably larger than the total F_2 value [Fig. 2(b)]. This implies that the present angular region is beyond the region of very small scattering angles which dominates the total cross sections. A comparison between the present F_2 values [Fig. 2(a)] and the previous F_2 values for capture and double ionization[10] reveals a dramatic shift of the peaks for simple double ionization towards larger θ, smaller peak values, and larger widths.

We find it difficult to explain the existence and position of the peaks in terms of any of the proposed ionization mechanisms. The kinematic restrictions of capture, which in TS-1 product a critical angle,[17,18] are not present for simple double ionization. More important, the peaks come at larger angles than the maximum scattering off a free electron. Therefore, the peak cannot be due solely to TS-1. To the extent that the deflection in the TS-2 mechanism is given by Coulomb scattering off the target nucleus, there is no reason to expect a peak from this mechanism at all. One of the double-ionization models invoking electron correlation does not treat close collisions[9] and, therefore, has little direct relevance for the present data. The other, more elaborate, theories,[7,8] which are formulated in the impact-parameter picture, do include close collisions and could conceivably yield angular differential F_2 values, but it is not obvious that a peak will emerge.

A structure in the angular-dependent probability for double ionization has been observed. We are not able to explain this in terms of the double-ionization mechanisms proposed in the analysis of total cross sections. However, two or more of these mechanisms may interfere and give rise to a structure like the one observed. This would be consistent with the previously cited works,[2,4,5] which presume interference at the very small deflection angles which dominate the total cross section. A more definite analysis awaits the completion of more detailed calculations.

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