Search for interference effects in the continuum electron energy spectrum from 2-MeV He^{++}-He collisions

M. M. Duncan, M. G. Menendez, and F. L. Eisele*
Department of Physics and Astronomy, University of Georgia, Athens, Georgia 30602

J. Macek
Behlen Laboratory of Physics, University of Nebraska, Lincoln, Nebraska 68508
(Received 25 October 1976)

The secondary-electron energy spectrum from He^{++}/He has been measured with sufficient resolution to observe interference effects predicted by a Faddeev treatment of charge transfer. No oscillations were seen in the experimental results.

The forward peaking of secondary electron distributions from ion-atom collisions, observed in proton-helium collisions,[1,2] has been interpreted as "charge transfer to continuum states".[3] The interpretation supposed that secondary electrons with velocities approximately equal to the projectile velocity are characterized by Coulomb wave functions centered on the projectile in much the manner that electrons picked up by the projectile in true bound states are characterized by bound-state wave functions centered on the target. In this picture, charge exchange to high-n states and ionization in the region of the forward peak are connected by the equation[4]

$$\frac{\partial^2\sigma}{\partial\Omega\partial E_e}=\bar{\sigma}_{ex}\frac{v_e}{|\vec{v}_e-\vec{v}_i|}\,, \qquad (1)$$

where $\bar{\sigma}_{ex}$ relates to the cross section for charge transfer to high-n states $\sigma_{ex,n}$ according to

$$\sigma_{ex,n}=\bar{\sigma}_{ex}/n^3\,. \qquad (2)$$

In Eq. (1), E_e is the energy of the electrons in the laboratory frame, $\vec{v}_e$ is their velocity and $\vec{v}_i$ is the velocity of the projectile.

Equation (1) is based on very general theoretical considerations and is fairly well established experimentally in that a peak of approximately the correct shape is observed at $\vec{v}_e\approx\vec{v}_i$; however, the influence of the charge-transfer contribution to the ionization cross section in a velocity region where it is comparable to the direct-ionization contribution is not well understood.

The major difficulty in obtaining a comprehensive theory is our lack of asymptotic wave functions for three charged particles. Several nonrigorous approximate theories have been proposed.[3,5-7] They generally divide into two distinct categories. In one category are those first-order theories which obtain separate amplitudes for the direct-ionization and the charge-transfer contributions.[3,7] The cross section, proportional to the square of the sum of the separate amplitudes, exhibits interference terms. In the second category are those theories which employ a single first-order amplitude,[5,6] equal to the normal Born amplitude away from the forward peak region but equal to some type of charge-transfer term near $\vec{v}_e\approx\vec{v}_i$. In this case the cross section shows no interference terms. The purpose of the investigations reported here is to experimentally search for interference effects in ionization cross sections and thereby give some guidance for theory.

Interference effects are most pronounced where the phase of the exchange cross section is varying rapidly owing to the Coulomb distortion of the final-state wave function, and where the direct-ionization and charge-transfer contributions are comparable. This suggests examining the structure of the forward peak at small, but not zero, electron ejection angles. Calculations based on the first approximation to Faddeev's equations[3] exhibit considerable structure in this region, as in Fig. 1 where the cross section at 1.6° for He^{++} +He collisions is plotted vs electron energy near the forward peak. Calculations at other angles also show structure, but 1.6° seemed to be optimal for observation. An angle of 1.6° is also convenient experimentally since at that angle the background due to electrons produced by ion bombardment of the apertures is negligible.

The measurements were made in the crossed beam apparatus described elsewhere.[2,8] A hemispherical analyzer with resolution $\Delta E/E=0.01$ (FWHM) was used to measure the electron energy spectra. The scattering geometry was dominated by the small diameter of the crossed beam which resulted in an overall angular resolution of approximately ±0.3°.

Figure 2 shows our results. The statistical

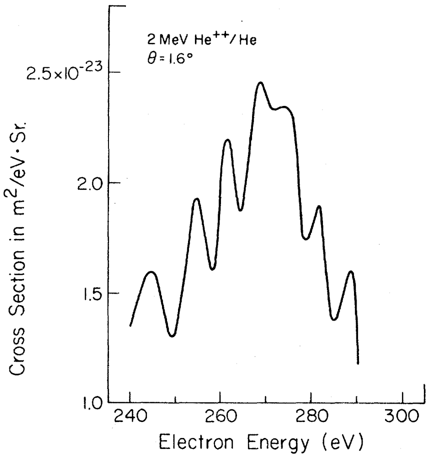

FIG. 1. A calculation of the DDCS at 1.6° showing the interference structure predicted by the first approximation to Faddeev's equations.

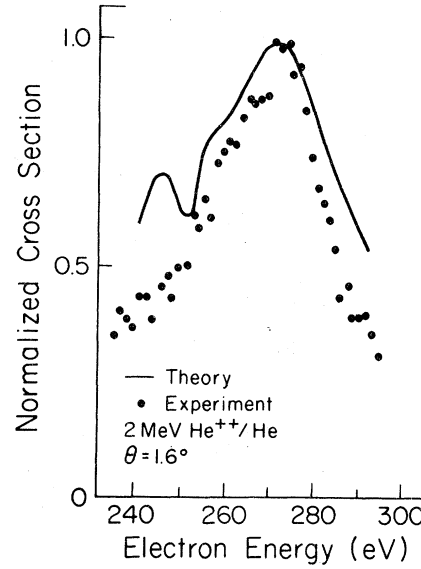

FIG. 2. DDCS of $v_e \sim v_i$ electrons normalized to peak values of 1. The solid curve is obtained by averaging the theoretical results over the energy and angular resolutions of the experimental apparatus. The data are shown as closed circles.

error of the data is about 5% at peak maximum. The experimental data are smooth within statistics and show no structure. The theoretical curve showing interference has been averaged over an angular interval of 0.6° and an energy interval of 2.5 eV which is approximately the energy resolution at the peak value. The only interference peak that survives the averaging over the angular interval is the one around 245 eV. The interference structure arises mainly from the rapidly oscillating phase of $\Gamma(1+iz/|\vec{v}_e-\vec{v}_i|)$ in the charge-exchange amplitude. Near $\vec{v}_e \approx \vec{v}_i$ one has

$$|\vec{v}_e-\vec{v}_i|^{-1}=[(v_e-v_i)^2+v_e v_i \theta^2]^{-1}. \quad (3)$$

Thus, the phase of the Γ function is very sensitive to θ when $v_e \approx v_i$ and averaging over θ tends to average out the structure. Alternatively, when $v_e - v_i$ is comparable to $(v_e v_i)^{1/2}\theta$, the average over θ results in less than one oscillation of the phase and some interference structure remains. The condition $v_e - v_i \approx (v_e v_i)^{1/2}\theta$ corresponds to $E_e \approx 250$ eV and at this energy the phase of Γ varies between 11 and 15 rad as θ varies between 1.3° and 1.9°. In contrast, at $E_e = 275$ eV the phase of Γ varies between 16 and 30 rad over the same angular interval. Thus the interference structure is averaged out near 275 eV but not near 250 eV.

Our measurements clearly do not show the pronounced interference peak at 245 eV predicted by the first-order Faddeev description. Since this peak is due to a rapidly oscillatory phase factor which is found in all theories of charge exchange to continuum states, the presence of interference structure is expected in any theory which adds amplitudes. The interference is reduced by averaging over both the direction and the energy of the outgoing electron consistent with the experimental resolutions, but does not disappear completely. Thus we conclude that the first-order Faddeev theory considerably overestimates the degree of interference. Indeed, our results are compatible with no interference at all and suggest that any description which adds amplitudes will overestimate the degree of interference.

*Present address: School of Physics, Georgia Institute of Technology, Atlanta, Ga. 30084.

[1]G. B. Crooks and M. E. Rudd, Phys. Rev. Lett. 25, 1599 (1070); K. G. Harrison and M. W. Lucas, Phys. Lett. 33A, 142 (1970); R. W. Cranage and M. W. Lucas, J. Phys. B 9, 445 (1976).
[2]M. M. Duncan and M. G. Menendez, Phys. Lett. 56A, 177 (1976).
[3]J. Macek, Phys. Rev. A 1, 235 (1970).
[4]M. E. Rudd, and J. Macek, Case Stud. At. Phys. 3, 49 (1972).
[5]A. Salin, J. Phys. B 2, 631 (1969).
[6]K. Dettman, K. G. Harrison, and M. W. Lucas, J. Phys. B 1, 269 (1974).
[7]Y. Band, J. Phys. B 7, 2557 (1974).
[8]M. G. Menendez, M. M. Duncan, F. L. Eisele, and B. R. Junker, Phys. Rev. A 15, 80 (1977).