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Convoy electrons for collisions between projectile He^+ and C foils from 17.5 to 25 keV/amu

T. C. Chu,[1] C. S. Lee,[2] C. C. Hsu,[3] Y. C. Chang,[3] J. L. Tsai,[3] and C. F. Pai[1]
[1]*Institute of Nuclear Science, National Tsing Hua University, Hsinchu, Taiwan 300, Republic of China*
[2]*Department of Physics, National Central University, Chungli, Taiwan 320, Republic of China*
[3]*Department of Physics, National Tsing Hua University, Hsinchu, Taiwan 300, Republic of China*

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Charge-analyzed He^+ and He^{2+} ions are measured in coincidence with convoy electrons for collisions between He^+ ions and carbon foils of 3 and 10 $\mu g/cm^2$. The bombarding energy of the projectile He^+ ranges from 17.5 to 25 keV/amu. The results are independent of the thickness of the carbon foils. The cross section of convoy electrons for He^{2+} is about 3% of that for He^+ in a state of equilibrium resulting from multiple excitations and deexcitations. The transport length λ_c of the convoy electrons is about 2.0 ± 1.2 Å, which is close to the mean free path of free electrons of the same speed in the carbon foil. This implies that the convoy electrons are produced in the bulk of the foil and survive scattering in a 2.0 ± 1.2-Å-thick last layer.

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I. INTRODUCTION

Convoy electrons produced by H^+ and He^+ ions passing through C foils have been extensively studied [1,2]. Kroneberger *et al.* [2] and Biedermann *et al.* [3] measured He^{2+}, He^+, and He^0 in coincidence with convoy electrons for incident He^+ energies of 100–200 keV/amu, and found that the relative convoy electron yields coincident with specific charge states are identical with the emerging charge state distributions within experimental error. They also determined the transport length λ_c and compared this with the mean free path of free electrons for the same speed, and discussed the production mechanism for convoy electrons. Their conclusion was that convoy electrons are produced inside the bulk of the C foil. However, there are no investigations for lower-energy regimes, such as tens of kev/amu; hence the study of the transport length to understand the mechanism of the convoy electrons is still interesting and important.

II. EXPERIMENT

He^+ ion beams were produced in a rf ion source and accelerated through a potential generated by the 100-kV Cockroft-Walton power supply at National Tsing Hua University. The beams were focused by an einzel lens, accelerated and then deflected through 45° by an analyzing magnet, and finally entered the collision chamber as described in a previous paper [4]. The beam line and chamber were differentially pumped to less than 4×10^{-8} and 3×10^{-7} Torr, respectively, to minimize neutralization of the ion beam prior to collisions with the carbon foil. The carbon foil thicknesses were 10 and 3 $\mu g/cm^2$. The convoy electrons were measured at $\theta=0°$ by a 127° cylindrical electrostatic energy analyzer (CEEA) with a spiraltron electron multiplier as described in Ref. [4]. In the present measurement, the half-angle of the angular acceptance cone of the cylindrical analyzer was set to about 10°, and the fractional energy resolution ($\Delta E/E$) was about 8%. The voltage bias of the analyzer was adjusted to steer the convoy peak onto the spiraltron; hence the convoy electrons around the peak of the energy distribution were measured. He ions exiting the carbon foil passed through a 5-mm-diam ϕ hole at the back of the 127° CEEA and a 0.8-mm-diamϕ hole at the end of a Faraday cup located 125 mm from the carbon target. Following the cup, the He ions were analyzed by a magnet to separate different charge states and were detected by a position-sensitive channel plate detector. The experimental arrangements are shown in Fig. 1. The signals of the channel plate went to the input of the MCA (multichannel analyzer) via a preamp, an amplifier, and a position sensitive detector analyzer. A coincidence requirement between the convoy electrons and the charge-analyzed He^{2+} and He^+ ions was imposed. The output of the coincidence logic went to the gate of MCA to measure the charge-analyzed He^+ and He^{2+} ions. Figure 2 shows a block diagram of the coincidence arrangement, and Fig. 3 shows a typical position spectrum for He^+ and He^{2+}. The beam currents were measured by a current integrator fed by the holder of carbon foil and the Faraday cup, and were estimated to be ~10 pA. The coincidence events were about 1–2 per second, and the coincidence yields were normalized to the charge of the current integrator.

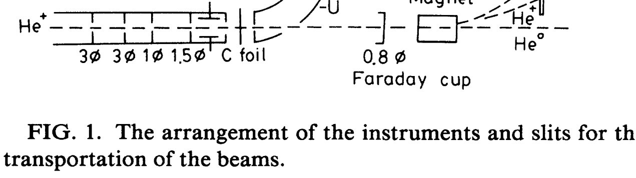
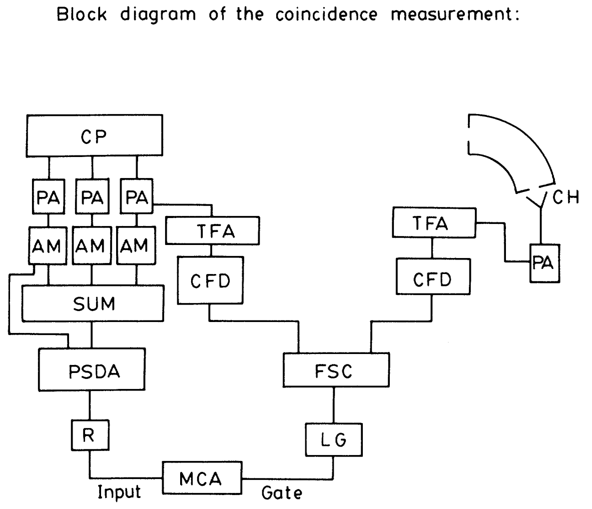


FIG. 1. The arrangement of the instruments and slits for the transportation of the beams.



CP: channel plate, CH: channeltron, PA: preamplifier,
AM: amplifier, SUM: sum invert amplifier,
PSDA: position sensitive detector analyzer,
CFD: constant fraction discriminator,
FSC: fast slow coincidence, LG: logic shaper,
MCA: multichannel analyzer, R: relay amplifier,
TFA: timing filter amplifier.

FIG. 2. A block diagram of the coincidence measurement.

III. RESULTS AND DISCUSSION

The partial yields of convoy electrons, coincident with analyzed He^+ and He^{2+} ions as a function of projectile energy, are shown in Fig. 4; the data include the results for carbon foils of 10 and 3 $\mu g/cm^2$. The solid lines are drawn to guide the eye. From the figure, we find that the partial convoy electron yields increase monotonically with impact energy. Most of the uncertainties of the present experiment arise from current losses in the Faraday cup, which has a 0.8-mm-diamϕ hole in the bottom. Accidental coincidences estimated from the background of the convoy electrons (i.e., δ electrons of the same velocity) and the resolving time (20 ns) of the coincidence circuit are about 15%. The total errors are estimated to be about 20% for these measurements.

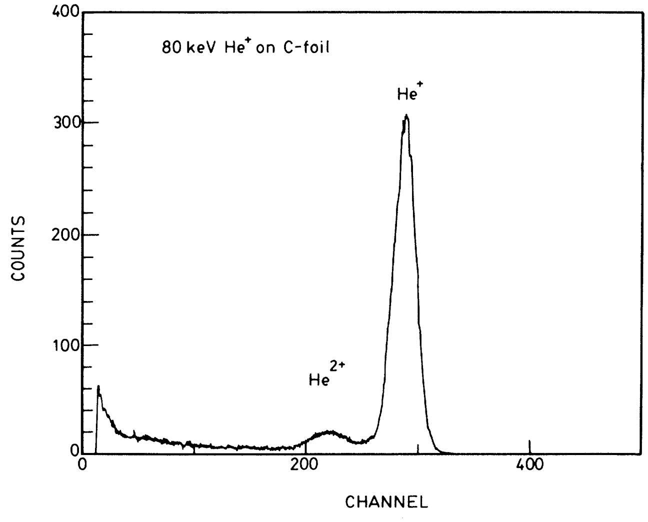


FIG. 3. A typical position spectrum for He^+ and He^{2+}.

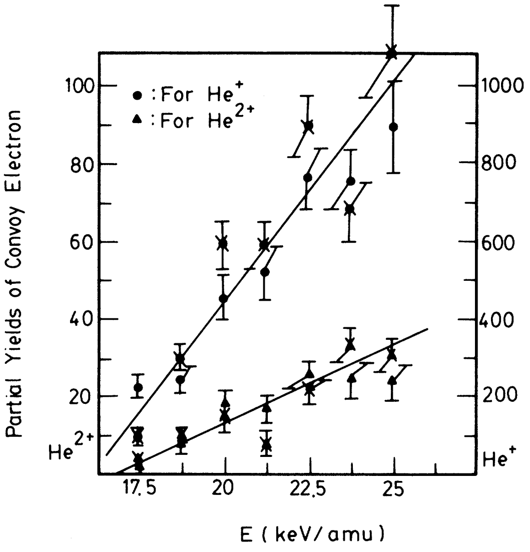


FIG. 4. Energy dependence of the yields of convoy electrons for exiting He^+ and He^{2+} ions, including the data for the targets of 3 (with x) and 10 $\mu g/cm^2$ (without x).

The ratio of the partial yields of convoy electrons with exiting He^+ and He^{2+} ions, i.e, $Y[He^{2+}]/Y[He^+]$, is shown in Table I. On the average, the ratios are constant at 0.027±0.005 independent of the helium-ion impact energy and the thickness of the carbon foil. The ratio of the equilibrium fractions $F_{2\infty}/F_{1\infty}$, i.e., the ratio of the yields of He^+ and He^{2+} ions exiting the C foil was also

TABLE I. The ratios of the charge fraction of He^{2+} and He^+ and $F_{2\infty}/F_{1\infty}$, and of the yields of the convoy electrons $Y[He^{2+}]/Y[He^+]$ for carbon foil of 10 and 3 $\mu g/cm^2$ (in parentheses).

He^+ beam energy (keV/amu)	$\frac{F_{2\infty}}{F_{1\infty}}$ (%)	$\frac{Y[He^{2+}]}{Y[He^+]}$ (%)
17.5	1.5 (3.3)	1.1 (4.5)
18.8	3.3 (3.3)	2.8 (3.6)
20.0	3.3 (2.1)	3.0 (2.5)
21.3	3.9 (3.3)	2.7 (1.3)
22.5	4.2 (3.4)	2.6 (2.5)
23.8	3.9 (2.4)	2.6 (2.6)
25.0	4.1 (2.5)	2.4 (2.5)
Average	3.2±0.6	2.7±0.5

measured directly at each impact energy as shown in Table I. Its average value is 0.032±0.006. This value is consistent with the value of 0.035, which is based on low-energy extrapolation of Table XV of Allision [5]. The ratio of Y[He^{2+}]/Y[He^{+}] is close to the ratio of $F_{2\infty}F_{1\infty}$ within errors.

This result is consistent with the result of Biedermann *et al.* [3], in which the yields of convoy electrons $Y_c(q_f)$ coincident with charge state q_f were found to be identical with the emerging charge-state distribution. Applying the theory of Mennedez *et al.* [6], we find the transport length of convoy electrons λ_c to be 2.0±1.2 Å using cross sections for electron capture and loss, and an equilibrium fraction estimated (with potentially large error bars) from Refs. [7] and [5]. ($\sigma_{12}=0.79\times10^{-17}$ cm^2/target atom, $\sigma_{21}=60\times10^{-17}$ cm^2/target atom, $F_{1\infty}=0.013\%$, and $\rho_c=9\times10^{22}$ atoms/cm^3). This length is close to the attenuation length of free electrons of the same speed [8], and is much less than the thickness of the targets employed.

IV. CONCLUSION

In the present study, we have shown that the ratio of the convoy electrons for scattering He^{2+} and He^{+} ions is independent of the thickness of C foil and comparable with the ratio of equilibrium fractions for He^{2+} and He^{+} ions. Hence the projectile ions first reach a charge-state equilibrium through multiple collisions in the bulk of the carbon foil. The convoy electrons of the projectile are produced in the bulk of the foil and finally survive scattering in a 2.0 ±1.2 Å-thick last layer. The cross section of convoy electron for the scattered He^{2+} ion is about 3% of that for scattered He^{+} ions in this studied energy regime. This conclusion is consistent with that of Biederman *et al.*, but extends that result to a lower collision energy regime.

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