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Production of recoil ions He^{i+} accompanied by single electron loss of 0.2–7 MeV C^{q+} and 0.25–5 MeV O^{q+} $(q = 1 - 4)$ ions*

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Target ionization accompanied with projectile electron loss is investigated for 0.2–7 MeV C^{q+} $(q = 1 - 4)$ with He and 0.25–5 MeV O^{q+} $(q = 1 - 4)$ with He collisions. For projectile single-electron loss channel, the He double-to-single ionization ratio R is nearly independent of projectile charge state but dependent on the nuclear charge of projectile $Z_{\rm p}$. The results are analysed with atomic structure qualitatively. So far there have not existed the experimental data comparable with our results, to our knowledge. The ratio R is interpreted in terms of the two-step mechanism. This analysis agrees well with similar experiments in the literature.

Keywords: ion-atom collision, cross-section, electron loss
PACC: 3450H

1. Introduction

In this work, the absolute cross sections of target ionization for projectile electron-loss channel in 0.2–7 MeV C^{q+}+He $(q = 1 - 4)$ and 0.25–5 MeV O^{q+}+He $(q = 1 - 4)$ collisions are investigated. Such studies can help test the theories of few-body problems arising from atomic physics, specifically the interactions of nuclei with atomic electrons, and the interactions of electrons with other electrons.[1] For this purpose, helium may be used as the simplest neutral target that shows electron–electron effects, while carbon and oxygen can serve as partially stripped projectiles.

For the energy range investigated here, double ionization is examined in terms of mechanisms involving electron-nucleus (independent-particle) interactions as well as electron-electron (correlation) effects.[1,2] The double ionization by independent-particle interactions can be understood as two separate interactions (in the same collision event) of the projectile nucleus with each of the target electrons; this picture is valid for such intermediate velocities (for which there is sufficient time for two interactions) that $Z/V \geq 0.2$ (Z is the projectile atomic number and V is the velocity in atomic units). For this case, Knudsen *et al*[3] found empirically that $R \propto (Z/V)^2 \ln(V)^{-1}$. For such velocity and charge that $Z/V \leq 0.1$,[1,2] the probability of double ionization by two separate projectile-nucleus–target-electron interactions in a single collision event becomes small, and double ionization is described in the 'sudden approximation' instead where after the first electron has been ejected by the projectile nucleus the atomic wave function of the target helium changes to the ionic wave function, remaining the second electron in its original atomic eigenenergy state. This electron can then be 'shaken off', due to the matrix element between the atomic state (containing the electron–electron interaction) and the asymptotic ionic state (without electron–electron interaction) being nonzero. For the latter process, the ratio R of double-to-single ionization is expected to be constant.[2]

At present, investigations are focused on highly charged ions colliding with noble gases[4–6] and on collisions at high energies.[7] Up to now, few experimental investigations have been devoted to studying the mechanisms of recoil-ion production when the loss of a number of the screening electrons of projectiles is accompanied simultaneously (loss ionization).

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2. Experimental procedure

This work is performed by using the 2×1.7MV tandem accelerator at Lanzhou University with the technique similar to that used previously.[8] A schematic illustration of the experimental setup is shown in Fig.1. The C^{q+} or O^{q+} ($q = 1 - 4$) beams emerging from the stripper are selected by switching magnet before entering the experimental line and are collimated through the gas cell. In the gas cell, some fraction of the incoming beam undergoes charge-changing collisions.

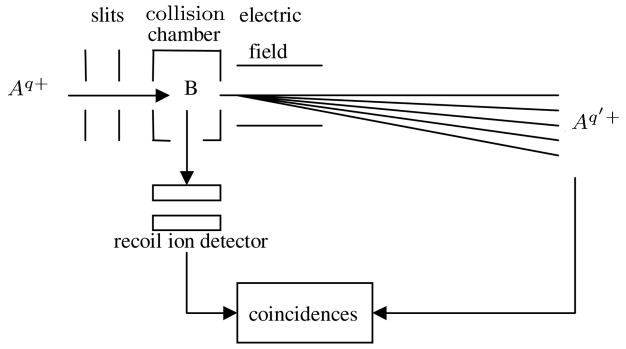


Fig.1. Schematic sketch of experimental arrangement.

With no gas in the cell, the background pressure in the line behind the switching magnet is less than 6×10^{-5} Pa. The pressure in the gas cell is measured by an absolute capacitance manometer. The pressure outside the gas cell is monitored by a Penning gauge.

The gas is bled into the cell through a needle valves, and its flux is monitored by a flowmeter. The average pressure in the cell with gas is controlled at 6.4×10^{-2} Pa. The pressures at the entrance and at the exit of the chamber with gas both are less than 5×10^{-4} Pa.

Outgoing charge-changed projectiles are separated by a transverse electrostatic field, and detected by a position-sensitive detector with a microchannel plate. The recoil ions He^{+} and He^{2+} are accelerated by a transverse electric field into a channel-electron-multiplier (CEM), where they generate the start signals for a time-to-amplitude converter (TAC). The time-of-flight technique is employed to measure the charge state of the recoil ions, with the signal of the recoil ion and the delayed scattered projectile signal used respectively as the start signal and the stop signal. Therefore coincidences can distinguish between the charge state of recoil ion and the charge state of outgoing projectile. The doubly differential spectra were recorded by using an MPA data-acquisition system.

Special concern is taken to ensure that the single-collision condition is satisfied and the recoil ions does not change their charge states during the period of flight.

As indicated in Ref.[9], when $(E/M)^{1/2} > 2$ $(\mathrm{keV/u})^{1/2}$ the efficiency of detector with microchannel plate is nearly 100%. For our energy range investigated, $(E/M)^{1/2}$ for outgoing projectile is larger than $4(\mathrm{keV/u})^{1/2}$. Therefore the detection efficiency for outgoing projectile is approximately 100%.

However, the detection efficiency for recoil ion should be scaled since our experimental values of $(E/M)^{1/2}$ are 0.5 $(\mathrm{keV/u})^{1/2}$ for He^{+} and $0.71(\mathrm{keV/u})^{1/2}$ for He^{2+} respectively. The cross section for any channel $\{Z_{\mathrm{P}}^{q}+Z_{\mathrm{T}} \rightarrow Z_{\mathrm{P}}^{q'}+Z_{\mathrm{T}}^{i}+(i+q'-q)e\}$ can be measured by Eq.(1)

$$\sigma_{qq'}^{i} = \frac{n_{qq'}^{i}/\eta_{\mathrm{r}}^{i}}{INLT}, \tag{1}$$

where $n_{qq'}^{i}$ is the intensity of coincidence event, η_{r}^{i} is the recoil-ion detection efficiency, I is the integrated beam intensity, N is the target-gas density, L is the interaction length, and T is the optical transmission of the recoil-ion detection system due to the grids used.

The double-to-single ratio of target ionization undergoing projectile single electron loss can be measured according to Eq.(2):

$$R_{q,q+1}^{21} = \frac{\sigma_{q,q+1}^{2}}{\sigma_{q,q+1}^{1}} = \frac{n_{q,q+1}^{2}/\eta_{\mathrm{r}}^{2}}{n_{q,q+1}^{1}/\eta_{\mathrm{r}}^{1}} = \frac{\eta_{\mathrm{r}}^{1}n_{q,q+1}^{2}}{\eta_{\mathrm{r}}^{2}n_{q,q+1}^{1}}. \tag{2}$$

For our experimental data the ratio of $\eta_{\mathrm{r}}^{1}/\eta_{\mathrm{r}}^{2}$ is 0.74 according to Ref.[9]. The absolute detection efficiency of recoil ion can be obtained by comparing our data with the data in Ref.[10]. According to Ref.[10], the total single capture cross section is 101Mb at $E = 2.0$ MeV in C^{3+} + He collision. Based on this scale, according to Eqs.(1), (2) and our experimental data for C^{3+} + He collision at $E = 2.0$ MeV, we obtain $\eta_{\mathrm{He}}^{1+} \approx 0.68$ and $\eta_{\mathrm{He}}^{2+} \approx 0.92$ for our experiment. Because the total single capture cross section is considerably large compared with others in the energy regime investigated, using the data in Ref.[10] to scale our detection efficiency can diminish our uncertainties due to it.

3. Results and discussion

Our results are presented in Tables 1 and 2. The uncertainties come mainly from the recoil ion

detection efficiency (∼5%), background fluctuations (∼2%), cited reference data (∼8%), effective length of the cell (∼5%), gas density (∼5%) and statistic error (3%−12%). The total uncertainties in Tables 1 and 2 are less than 17%.

Table 1. Cross sections for single and double ionizations and ratios for double-to-single ionization of He by C^{q+} $(q = 1 - 4)$ projectile undergoing single-electron loss.

V/v_0	$\sigma^{01}_{q,q+1}$/Mb	$\sigma^{02}_{q,q+1}$/Mb	$R^{21}_{q,q+1}$
	C^{1+} projectile		
1.2	29.6	1.00	0.0339
1.3	27.2	1.11	0.0407
1.4	43.3	1.95	0.0451
1.6	40.1	2.82	0.0703
1.8	43.7	4.08	0.0933
2.0	45.5	5.41	0.119
2.2	34.6	4.98	0.144
	C^{2+} projectile		
1.6	13.5	0.75	0.0553
1.8	19.8	1.71	0.0863
2.0	14.2	1.76	0.124
2.2	13.8	1.90	0.138
2.4	20.0	3.84	0.192
2.6	21.3	4.05	0.190
2.8	29.4	6.17	0.210
3.0	46.2	11.2	0.242
3.2	41.6	10.5	0.253
3.4	17.2	4.13	0.234
3.6	12.8	3.33	0.260
	C^{3+} projectile		
1.9	2.41	0.253	0.105
2.0	3.50	0.324	0.0925
2.2	8.90	1.07	0.120
2.4	12.8	1.74	0.136
2.6	13.3	2.22	0.171
2.8	15.4	2.79	0.181
3.0	17.2	4.71	0.274
3.2	19.3	5.13	0.266
3.4	19.5	5.32	0.273
3.6	20.8	5.01	0.241
3.8	21.8	5.01	0.230
4.0	18.6	4.97	0.267
4.2	17.3	4.26	0.246
	C^{4+} projectile		
3.4	10.1	2.97	0.294
3.6	7.96	2.56	0.321
3.8	6.45	1.65	0.256
4.0	7.27	2.14	0.295
4.2	11.0	2.94	0.267
4.4	7.27	2.26	0.311
4.6	6.31	1.63	0.258

Table 2. Cross sections for single and double ionizations and ratios for double-to-single ionization of He by O^{q+} $(q = 1 - 4)$ projectile undergoing single-electron loss.

V/v_0	$\sigma^{01}_{q,q+1}$/Mb	$\sigma^{02}_{q,q+1}$/Mb	$R^{21}_{q,q+1}$
	O^{1+} projectile		
1	18.5	0.568	0.0307
1.1	57.7	2.23	0.0387
1.2	59.2	2.73	0.0461
1.3	58.0	2.67	0.0562
1.4	40.6	2.51	0.0619
1.6	30.5	2.64	0.0865
1.8	24.5	2.62	0.107
	O^{2+} projectile		
1.3	7.91	0.328	0.0415
1.4	13.7	0.767	0.0560
1.6	31.7	3.42	0.108
1.8	35.3	3.99	0.113
2.0	44.2	6.41	0.145
2.2	63.8	11.5	0.180
2.4	70.5	13.1	0.186
2.6	45.1	9.83	0.218
2.8	46.3	10.5	0.226
3.0	48.5	13.6	0.281
3.2	47.5	12.4	0.261
	O^{3+} projectile		
2.0	9.23	1.38	0.150
2.2	15.4	2.76	0.179
2.4	14.6	2.50	0.171
2.6	12.3	3.24	0.237
2.8	15.0	4.02	0.268
3.0	19.7	4.67	0.237
3.2	30.7	8.47	0.276
3.4	40.9	12.2	0.298
3.6	28.9	8.41	0.291
	O^{4+} projectile		
3.4	33.9	9.63	0.284
3.6	23.2	8.05	0.347
3.8	23.0	7.02	0.305
4.0	15.9	4.80	0.302

The antiscreening effect can be estimated according to the ionizations of e+He and e+He^+. Those data were obtained by Kim and Rudd.[11] However, the antiscreening effect cannot be applied to our collision system directly because there exists no free electron on the projectile ion. This effect (electron–electron effect) cannot be separated from the screening effect (electron–nucleus interactions) quantitatively. Therefore our values of the ratio R^{21} include both of them.

Of primary interest in this work is the ratio R of double-to-single ionization cross-section of He for

the projectile electron loss channel, because this ratio can be used to exhibit the main features of double ionization.[1−3,12,13] Double ionization is generally expected to requires a smaller impact parameter in collisions than single ionization. For fully stripped projectiles with such nuclear charge Z and velocity V that $Z/V \leq 1$ (V in atomic units), the ratio R of double-to-single ionization has been studied.[2,3,12,13] The validity of this scaling for fully stripped projectiles at intermediate-to-high velocities has been well established.[12] For $Z/V \geq 0.2$, Knudsen *et al*[3] found empirically that $R \propto (Z/V)^2 \ln(V)^{-1}$. In contrast, little is known about the behaviour of R for projectiles which are not fully stripped. For our investigation of $Z/V = 1 - 8$ ($q/V = 0.2 - 4$), it is not clear whether it should be also valid for partially stripped projectiles. Therefore the two-step mechanism (independent-particle ionization) and the shake-off mechanism have to be justified for loss ionization in this energy range. Our results about the ratio are shown in Figs.2 and 3.

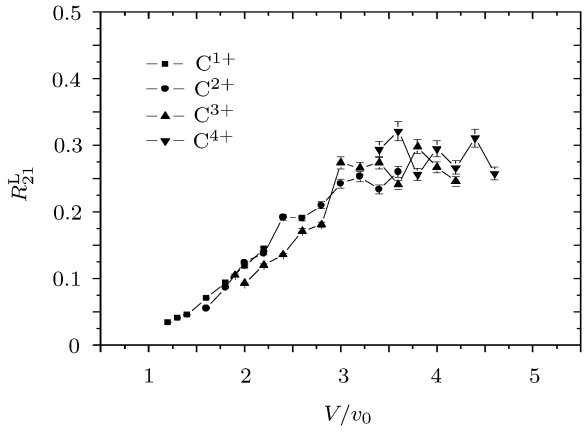


Fig.2. He target double-to-single ionization cross section ratios associated with single-electron loss for C^{q+} projectiles.

The relative uncertainties in Figs.2 and 3 come mainly from the statistic error (3%−12%) and the recoil ion detection efficiency error (∼5%). The total absolute uncertainties are labelled in Figs.2 and 3.

The results of Figs.2 and 3 suggest that the electrons on the projectile have little influence on the ratio of double-to-single He ionization. This conclusion agrees well with the data in Refs.[14,15]. The ratio R for O^{q+} is generally larger than that for C^{q+}. This suggests that the ratio R is interrelated to the electronic structure of projectile. The qualitative analysis is as follows.

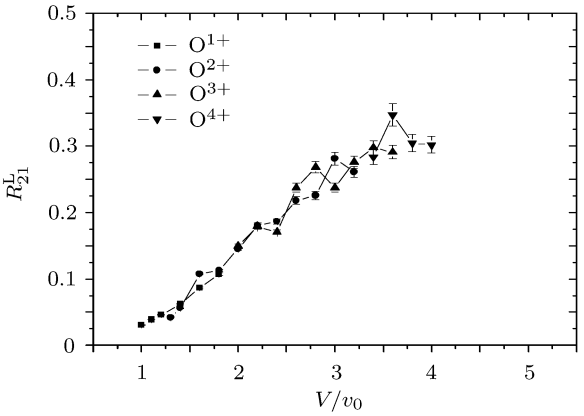


Fig.3. He target double-to-single ionization cross section ratios associated with single-electron loss for O^{q+} projectiles.

The process of He ionization accompanied by projectile single electron loss can be expressed as

$$A^{q+} + \mathrm{He} \rightarrow A^{(q+1)+} + \begin{cases} \mathrm{He}^{1+} + 2\mathrm{e}, \\ \mathrm{He}^{2+} + 3\mathrm{e}, \end{cases}$$

where A is C^{q+} or O^{q+} ($q = 1 - 4$). According to the two-step mechanism and the antiscreening theory, the double ionization process of He for the loss channel can be regarded as single direct ionization of $He^+$by the projectile ion $A^{(q+1)+}$ as follows:

$$A^{(q+1)+} + \mathrm{He}^{1+} \rightarrow A^{(q+1)+} + \mathrm{He}^{2+} + \mathrm{e}.$$

According to this picture, the ratio $R^{21}_{q,q+1}$ for target ionization accompanied by projectile single electron loss is deduced as

$$R^{21}_{q,q+1} = \frac{\sigma^{\mathrm{L}}_{\mathrm{DI}}}{\sigma^{\mathrm{L}}_{\mathrm{SI}}} = \frac{\sigma^{\mathrm{L}}_{\mathrm{SI}} P^{\mathrm{I}}_{\mathrm{He}^+}}{\sigma^{\mathrm{L}}_{\mathrm{SI}}} = P^{\mathrm{I}}_{\mathrm{He}^+}. \qquad (3)$$

The ionization of He^+ is expected to occur at a small parameter b. Therefore the value of effective charge q_{eff} of projectile ions for the same Z_{p} seen by He^+ should be the same in this energy region and those for different Z_{p} seen by He^+ are different. Undoubtedly, the values of q_{eff} of O^{q+} seen by He^+ should be larger than that of C^{q+}. Therefore, the value of ratio R for O^{q+} should be larger than that for C^{q+}. As shown in Figs.2 and 3, the ratio R is independent of q but interrelated to Z_{p}, which agrees with this analysis.

This analysis can be applied to other collision systems such as Li^{q+}+He or He^++He and acquires good agreement.[14,15] The validity of this analysis indicates that the two-step mechanism is valid whereas

the shake-off mechanism is invalid. The reason is that the shake-off mechanism suggests a constant for the ratio $R^{21[2]}$ as described in the introduction.

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