IONISATION OF HELIUM BY MULTIPLY CHARGED IONS AT INTERMEDIATE AND HIGH ENERGIES

P.D. FAINSTEIN(1), V.H. PONCE and R.D. RIVAROLA*

Centro Atomico Bariloche and Instituto Balseiro. RA-8400 Bariloche, Argentina
*Instituto de Fisica Rosario, Consejo Nacional de Investigaciones Cientificas y Tecnicas and Universidad Nacional de Rosario, RA-2000 Rosario, Argentina

Abstract

In the present work we study the single ionisation of Helium by $C^6+$ and $O^8+$ ions at intermediate and high impact energies. Calculations of double differential, single differential and total cross sections with the Continuum Distorted Wave-Eikonal Initial State model are presented. These results are compared with the experimental and theoretical results available.

Introduction

Recent experimental work has concentrated on the measurements of the angular and energy distributions of electrons ejected in collisions between bare multiply charged ions with Helium /1,2/. The use of several multiply charged ions with different impact energies allows to variate two of the fundamental parameters of the collision. These experiments have been performed for high impact energies while the projectile charge range from 6-10 /1/ to 40 /2/ which allows to variate the strength of the projectile potential and then to test its effect on the final electronic distribution.

Theoretical models have been developed in order to study this electronic emission. The most widely used is the first Born approximation (FBA) /2,3/. This model, which in some particular situations yields good results, was shown /4/ to have a basic deficiency in the treatment of three body coulomb interactions. This is related to an incorrect treatment of the distortion introduced by the projectile potential in the entrance and exit channels. In order to make a correct description of the three body coulomb interaction the Continuum Distorted Wave-Eikonal Initial State (CDW-EIS) model was recently introduced /5/. This model has been applied to ionisation of Helium by several multiply charged ions /2,6,7/ and by antiprotons /6,8/. The calculations together with the available experimental data show that even at high energies the FBA provides an incomplete picture of the physical process.

In this work we present calculations of double differential (DDCS), single differential (SDCS) and total cross sections (TCS) for ionisation of Helium by $C^6+$ and $O^8+$ ions.

(1) Presently at Laboratoire des Collisions Atomiques, Université de Bordeaux I, 351 Cours de la Libération, F-33405 Talence, France
Theoretical Model

We consider the ionisation of a multielectronic atom of nuclear charge $Z_p$ with $N+1$ electrons by a projectile of nuclear charge $Z_t$. Considering that there is only one active electron, while the rest remain frozen during the collision, we obtain analytical results for the transition amplitude $|\langle \gamma | t | \alpha \rangle |$. The CDW-EIS model is an improvement over theories such as the FBA because it takes into account the long range nature of the coulombic potential. It considers that the active electron is always in the presence of a two center potential given by the coulombic potentials of the target and projectile nuclei. This physical situation, which has been termed Two Center Electron Emission (TCEE), is considered within the distorted wave formalism by satisfying the correct boundary conditions for the initial and final state. It must be noted that the effect of the two center potential is always present and that neither can be neglected. This is clearly demonstrated by the presence of the ECC (Electron Capture to the Continuum) peak $/4/$ and of a ridge $/9/$ between the soft collision peak and the ECC peak. In the CDW-EIS model the initial state is proposed as a product of a bound state wavefunction, assumed as a linear combination of Slater type orbitals, centered on the target and an eikonal phase arising from the projectile-active electron interaction. The final state is represented by a product of hydrogenic continuum wavefunctions centered on the target and on the projectile. In this way the continuum centered on the target has been approximated by an effective coulomb potential with an effective charge fixed by the initial binding energy $(Z_{st}Z_{tu})^{1/2} = 1.3549$ $/7/$. In the FBA the initial and final states correspond to stationary states centered on the target. Then in this approximation the ionisation process is viewed as an excitation to the continuum. In the FBA it is easy to obtain the dependence of the cross sections on the projectile charge, which is given by a $Z_t^2$-scaling law. Then TCEE can be studied by looking for deviations from the $Z_p^2$-law.

Results and Discussions

In figure 1 we present the ratio between DDCS for impact of $C_6^+$ and $C_8^+$ with those for impact of $H^+$ with the same velocity (5 MeV/amu) as a function of the ejected electron energy for fixed electron ejection angles of $30^\circ$, $90^\circ$ and $150^\circ$ divided by $Z_p^2$. The FBA gives a constant factor of one for these ratios independent of the electron ejection energy and angle. The CDW-EIS model presents the same behaviour as the experimental data $/7/$. In the forward (backward) direction the ratio is enhanced (reduced) due to the strong attraction produced by the projectile potential. In the forward direction this effect reaches its maximum in the region of the ECC peak, where the projectile potential influence is strongest. At higher energies, and also in the forward direction, the ratio decreases and reaches the value one at an energy corresponding to the binary peak. The deviations with respect to the experimental data suggest that the discrepancies with the FBA increase because the FBA only considers a coulomb potential with charge $Z_t$. This is confirmed by the fact that as the electron energy increases the deviations from the FBA also increase. This may happen because as the electron energy increases the ejected electron starts to feel a coulombic potential due to the charge $Z_p + Z_t$. As in this case $Z_p > Z_t$, the discrepancies with the FBA increase because the FBA only considers a coulomb potential with charge $Z_t$. Unfortunately, measurements have been made for ejection energies up to 1 keV. It would be welcome to have measurements at higher ejection energies or at lower projectile impact energy (for example 1 MeV/amu) to test this part of the two center potential.
In figure 2 we present the ratio of SDCS for impact of C6* and O8+ with those for impact of H+ with the same velocity (5 MeV/amu) as a function of the electron ejection angle and divided by $Z_p^2$. The FBA gives a constant factor of one for these ratios. On the contrary, the CDW-EIS calculations show deviations in all the angular distribution. The deviations increase as the projectile charge increase.

In figure 3 we present total cross sections for ionisation of Helium by C6* and O8+ ions with impact energies from 50 keV/amu to 10 MeV/amu. Our calculations are compared with experimental data /10,11/ and with recommended data obtained from a combination of experimental data and theoretical calculations /12/. At high the FBA increase as the projectile charge increase.

**Figure 1**: DDCS ratio / $Z_p^2$. Theoretical results: (---) CDW-EIS for C6* impact; (——) CDW-EIS for O8+ impact; (---) FBA.

**Figure 2**: SDCS ratio / $Z_p^2$. Theoretical results: (---) CDW-EIS for C6* impact; (——) CDW-EIS for O8+ impact; (---) FBA.
energies our calculations are in agreement while at intermediate energies there are differences with previous results and experiments. The data are very scarce, so a definite comparison is not possible.

Figure 3: TCS for ionisation of He. Theoretical results: (---) present CDW-EIS; (- - -) ref. /12/. Experimental data: (*) ref. /10/; (▲) ref. /11/.

Figure 4: TCS ratio / $Z_p^2$. Theoretical results: (---) present CDW-EIS; (- - -) FBA.
In figure 4 we present the ratio of TCS for impact of \text{C}^6^+ and \text{O}^8^+ with that for impact of H\textsuperscript+ with the same velocity. The FBA gives a constant factor for these ratios due to the Z^2\textsuperscript- law. At high energies the CDW-EIS results reach these values. We have included in the figure previous results /6/ for impact of He\textsuperscript2\textsuperscript+ and Li\textsuperscript2\textsuperscript+. As the projectile charge increases the impact energy at which the CDW-EIS results reach the FBA values also increase. At intermediate energies the ratio decreases and the ratios are higher for the lower projectile charges. This effect has been termed the "binding effect" /13/ and together with the "polarization effect" /13/ it has been introduced to explain the deviations from the FBA in asymmetric systems where Z_p < Z_t. It is interesting to note that the CDW-EIS model has been applied to symmetric systems (Z_p = Z_t, /6/) and to asymmetric systems (Z_p < Z_t, /14/; Z_p > Z_t, /7/, present work). In all these systems we find deviations from the FBA. The results obtained with the CDW-EIS model can then be analysed in terms of binding and polarization effects but it must be noted that in the theoretical treatment there are no hypothesis related to them. Then we conclude that these effects are related to TCEE and that the CDW-EIS model accounts for the deviations respect to the FBA because it includes, in first order, the distortion due to the projectile coulombic potential.

Conclusions

In the present work we have shown various applications of the CDW-EIS model. These and previous calculations show that the CDW-EIS model gives accurate cross sections and is a useful tool to understand the experimental data. New measurements are needed to test the model, and some have been proposed in the present work. Data for TCS are very scarce and there are no measurements of SDCS. the present work shows some effects that may be interesting to look for them in measurements. More information can be obtained from DDCS. In this case the measurements of electrons ejected in the backward direction or with high ejection energy can show interesting aspects of the ionisation process.

References

/14/ P.D. Fainstein, V.H. Ponce and R.D. Rivarola, XIV Summer School and International Symposium on the Physics of Ionized Gases, (Sarajevo, 1988).