JP0055407

Ion–Ion Collisions

Erhard Salzborn[1] and Frank Melchert[2]

[1] *Institut für Kernphysik, Justus Liebig Universität, 35392 Giessen, Germany*
[2] *Physikalisch-Technische Bundesanstalt, 38116 Braunschweig, Germany*

Abstract. Collisions between ions belong to the elementary processes occurring in all types of plasmas. In this article we give a short overview about collisions involving one–electron systems. For collisions involving multiply–charged ions we limit the discussion to one specific quasi one–electron system.

1 Introduction

In recent years, the impetus for accurate cross section data for ion–ion collisions at energies in the keV–range has become great due to the research in thermonuclear fusion using either magnetic or inertial confinement. In magnetically-confined fusion plasmas, ion-ion reactions may provide effective tools for plasma diagnostics. Furthermore, the fusion plasma needs auxiliary heating by injection of powerful neutral hydrogen beams. Negative hydrogen ions H^- accelerated to energies of several $10^5 eV$ can be neutralized most effectively in so-called plasma-neutralizers [1] where the interaction between H^- and multiply-charged plasma ions X^{q+} dominates the neutralization process.

2 Experimental Method

The *crossed–beams* experiment used for the investigation of charge–changing ion–ion collisions was described in full detail earlier [5]. The experimental arrangement consists of an ultra-high vacuum chamber (typically $5 \cdot 10^{-11}$ mbar), a 'slow' (up to 20 kV) and a 'fast' (up to 200 kV) beam line. Both ion beams are produced in Electron Cyclotron Resonance ion sources. After momentum analysis they are collimated and made to intersect at an interaction angle of $\theta = 17.5^o$. Because of the low momentum transfer involved in the collision the reaction products remain within the parent ion beam after the interaction. They are separated from the incident ions by a two–step electrostatic deflector for each beamline and counted in single particle detectors. A time conincidence technique is employed to distinguish between background events from charge–changing reactions with the residual gas and true ion–ion signals.

3 One–Electron Systems

The investigation of collisions between protons and singly-charged helium ions is of considerable interest in plasma physics. Not only do these encounters occur inevitably in fusion plasmas but they also represent the simplest ion-ion collision system involving only one electron. Description of electron capture σ_C

$$H^+ + He^+ \longrightarrow H^0 + He^{2+} \qquad (1)$$

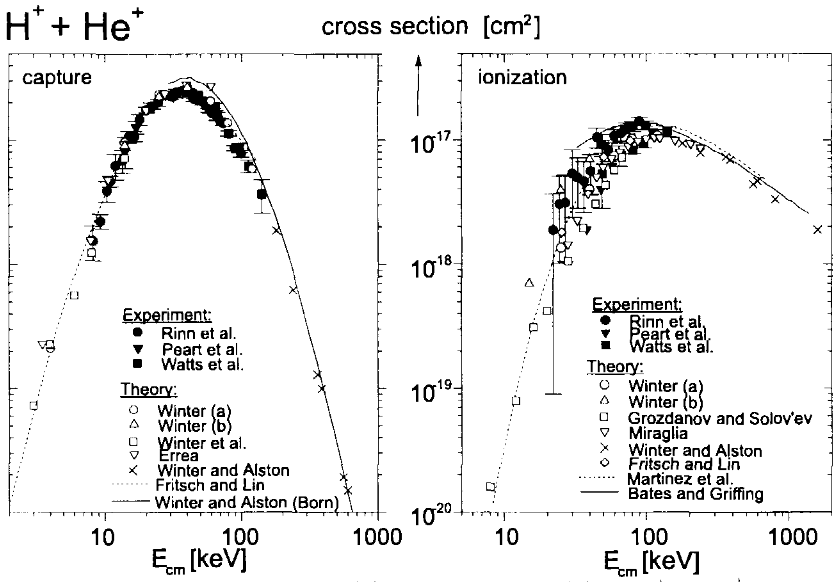

Figure 1: Cross sections for electron capture (1) and ionization (2) in $H^+ + He^+$ collisions, as a function of the cm-collision energy E_{cm}. Experimental *crossed-beams* results by Rinn et al. [2, 3], Peart et al. [6] and Watts et al. [7]. Most theoretical results are obtained by close-coupling (CC) calculations: Winter (a) [8]: Sturmian basis and pseudostates; Winter (b) [9]: 3-center atomic orbital (AO) basis; Winter et al. [10]: MO basis; Errea [11]: molecular orbital (MO) basis; Winter and Alston [17]: high energy CC; Fritsch and Lin [13, 14]: AO^+ basis; Grozdanov and Solov'ev [15]: MO basis; Miraglia [12]: CDW; Martinez et al. [16]: CDW-EIS; Winter and Alston [17] and Bates and Griffing [18]: Born approximation.

and ionization σ_I

$$H^+ + He^+ \longrightarrow H^+ + He^{2+} + e^- \tag{2}$$

is therefore an ideal testing ground for different theoretical models.

Three experimental groups [6, 7, 2] have studied these collisions independently and their experimental cross sections are compared with theory in Fig.1. In the high energy limit, the Born approximation is valid while for lower energies the continuum distorted wave calculation CDW-EIS with eikonal initial states by Martinez et al. [16] agrees as perfect with the ionization data as the atomic orbital AO^+ calculation by Fritsch and Lin [13] with the capture results. Since various authors confirm these findings, total cross sections for the reactions (1) and (2) are well described by theory.

For about two decades, theory was tested by comparing calculated and measured total cross sections. The first angular differential cross section has been measured by Kruedener et al. [4] for the electron capture of α-particles from He^+ ions:

$$He^{2+} + He^+ \longrightarrow He^+ + He^{2+} \tag{3}$$

This one-electron, charge-symmetric collision is resonant for $1s \rightarrow 1s$ electron capture and provides a unique testing ground for the study of the long-range Coulomb interaction in the quantum three-body problem. Kruedener et al. found an oscillatory structure the differential cross section $d\sigma/d\Omega$, plotted in Fig.2 as a function of the cm-scattering angle ϑ_{cm}.

In addition to the minimum in forward direction, another four minima of $d\sigma/d\Omega$ are resolved experimentally. The oscillation period increases with scattering angles. Forster et al. [19] used a semiclassical eikonal calculation which describes well the experimental data for low scattering angles ϑ_{cm}, but "runs out of phase" for larger ϑ_{cm}. The observed oscillatory structures in the differential electron capture cross section can be interpreted

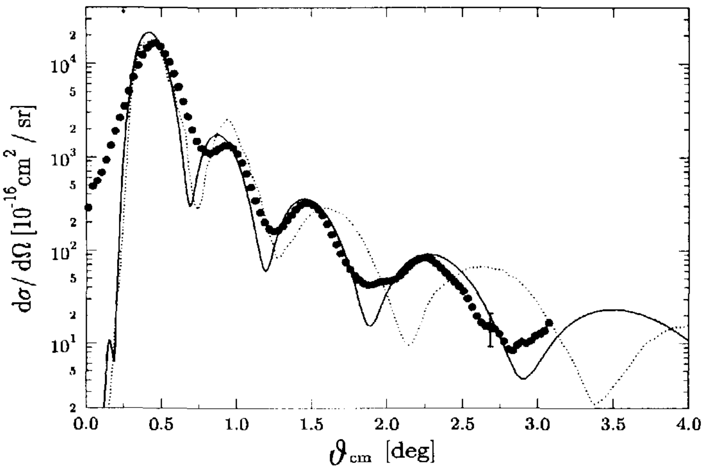

Figure 2: Angular differential cross sections for the electron capture (3) in $He^{2+} + He^{+}$ collisions at $E_{cm} = 2.5keV$. •: experiment, Kruedener et al. [4]; dotted line: semiclassical calculation, Forster et al. [19]; solid line: quantal calculation, Uskov and Presnyakov [4].

as interference between *gerade* and *ungerade* electronic states of the ionic molecule. Uskov and Presnyakov [4] presented a quantum approach based on a partial wave analysis using a molecular basis and delivered a very good description of the experimental data. We note that theory and experiment are compared on an absolute scale.

4 Collisions between Multiply-Charged Ions

Ion-ion collision data required for various applications are sparse; for collisions between multiply-charged ions they are practically absent. It is due to the recent development of powerful Electron Cyclotron Resonance (ECR) ion sources that *crossed-beams* experiments can be carried out with intense beams of multiply-charged ions. Up to now, however, only a few experiments, in which at least one ion carries a charge higher than one, have been performed.

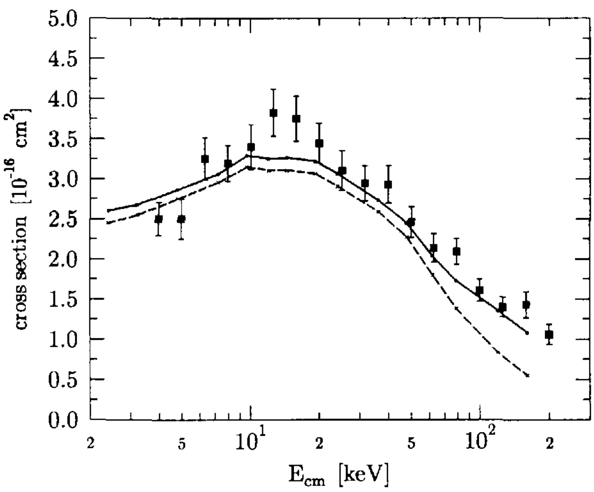

Figure 3: Cross sections for electron capture (4) in $^{3}He^{2+} + ^{13}C^{3+}$ collisions. Experimental data points by Melchert et al. [20] include 90% of statistical error. Close coupling calculation by Sidky and Lin [20] for capture to all He^{+} states (solid curve) and to the $He^{+}(1s)$ state only (dashed curve).

Here, we limit the discussion to electron capture in the quasi-one-electron collision system

$$^{3}\mathrm{He}^{2+} + ^{13}\mathrm{C}^{3+} \longrightarrow {}^{3}\mathrm{He}^{+} + ^{13}\mathrm{C}^{4+} \tag{4}$$

which was experimentally studied by Melchert at al. [20] and calculated by Sidky and Lin [20]. In their close-coupling calculation Sidky and Lin expand the active electron wave function as a sum of atomic states on both charge centers. The two inner electrons of the lithium-like C^{3+} ion are inert and enter as a model screening potential for the outer active electron. In Fig.3 measured and calculated cross sections are compared. Up to a collision energy of 50 keV the capture goes primarily to the $He^{+}(1s)$ channel, since the $He^{+}(1s)$ level is closest to the initial C^{3+} binding energy. As soon as one reaches the matching velocity, where the incoming He^{2+} ion is traveling at about the average speed of the C^{3+} valence electron, the capture spreads to other states of He^{+}, and the $1s$ state represents only half of the total capture probability (at $E_{cm} = 150\ keV$).

References

[1] A.S. Schlachter, K.N. Leung, J.W. Stearns, R.E. Olson: In *Production and neutralization of Negative Hydrogen Ions and Beams*, ed. by J.G. Alcsi, AIP Conference Proceedings No. 158 (Brookhaven 1986) 631

[2] K. Rinn, F. Melchert, E. Salzborn: J. Phys. B **18**, 3783 (1985)

[3] K. Rinn, F. Melchert, K. Rink, E. Salzborn: J. Phys. B **19**, 3717 (1986)

[4] S. Kruedener, F. Melchert, K. v.Diemar, A. Pfeiffer, K. Huber, E. Salzborn, D.B. Uskov, L.P. Presnyakov: Phys. Rev. Lett **79**, 1002 (1997)

[5] S. Meuser, F. Melchert, S. Kruedener, A. Pfeiffer, K. v.Diemar, E. Salzborn: Rev.Sci.Instrum. **67**, 2752 (1996)

[6] B. Peart, K. Rinn, K. Dolder: J. Phys. B **16**, 1461 (1983)

[7] M.F. Watts, K.F. Dunn, H.B. Gilbody: J. Phys. B **19**, L355 (1986)

[8] T.G. Winter: Phys. Rev. A **35**, 3799 (1987)

[9] T.G. Winter: Phys. Rev. A **37**, 4656 (1988)

[10] T.G. Winter, G.J. Hatton, N.F. Lane: Phys. Rev. A **22**, 930 (1980)

[11] L.F. Errea, J.M. Gomez-Llorente, L. Mendez, A. Riera: J. Phys. B **20**, 6089 (1987)

[12] J.E. Miraglia: Phys. B **16**, 1029 (1983)

[13] W. Fritsch, C.D. Lin: J. Phys. B **15**, 1255 (1982)

[14] W. Fritsch, C.D. Lin: In *Thirteenth International Conference on the Physics of Electronic and Atomic Collisions* (Berlin 1983), Abstract of Contributed Papers, p 502

[15] T.P. Grozdanov, E.A. Solov'ev: Phys. Rev. A **38**, 4333 (1988)

[16] A.E. Martinez, R. Deco, D. Rivarola, P.D. Fainstein: Nucl. Instr. Meth. in Phys. Res. B **43**, 24 (1989)

[17] T.G. Winter, S.G. Alston: Phys. Rev. A **45**, 1562 (1992)

[18] D.R. Bates, G.W. Griffing: Proc. Phys. Soc. London **A 66**, 961 (1953)

[19] C. Forster, R. Shingal, D.R. Flower, B.H. Bransden, A.S. Dickinson: Phys. B **21**, 3941 (1988)

[20] F. Melchert, S. Meuser, S. Kruedener, A. Pfeiffer, K. v.Diemar, E. Salzborn, E.Y. Sidky, C.D. Lin : J.Phys.B: At.Mol.Opt.Phys.**30**, L697 (1997)