ANGULAR SCATTERING EFFECTS IN ELECTRON CAPTURE BY MULTIPLY CHARGED IONS

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Abstract

Energy-gain measurements have been performed on single-electron capture reactions with low-energy heavy multiply charged ions colliding with He. Because of the large mass ratio between projectile and target, a non-negligible recoil energy is taken up by the target. This results in energy-gain spectra that are shifted and deformed in such a way that they are difficult to resolve into contributions from different reaction channels unless a theoretical analysis including angular scattering effects is performed. We have developed a multichannel model for this purpose which also produces angular differential cross sections. An analysis has been made of the angular scattering present in the collision systems and theoretical energy gain spectra have been used in the assignment of reaction channels. As particular cases we show results from 300 eV $O^{2+}$ and $200-2000$ eV $Kr^{6+}$ ions capturing one electron from He.

1. Introduction

Charge exchange between multiply charged ions and neutral species is a reaction which might influence a wide range of astrophysical and laboratory plasmas (1). Line emission from excited ions formed through charge exchange is also an important diagnostic tool for these plasmas. Dalgarno and Butler (2) summarized charge transfer processes involving multiply charged ions at thermal energies that are likely to be important in studies of astrophysical plasmas. Recently Tawara and Phaneuf (3) reviewed the data needs for the edge region of magnetically confined fusion plasmas. They underlined the importance of state-selective studies of electron capture from hydrogen and helium by multiply charged ions at low energies.

In this work we report on investigations of single charge-exchange collisions between multiply charged ions and neutral He atoms at low impact energies. The state-selective method used is translational energy-gain spectroscopy. As projectiles in these studies we have used oxygen in charge states between 2 and 5 (4) and the heavy rare gases Ne through Xe in charge state 6 (5). The impact energies have typically been in the range 200-2000 eV. We compare our experimental results with a semiclassical collision model (6) to interpret the energy-gain spectra. To explore the angular scattering effects we have also calculated angular differential cross sections for 300 eV $O^{2+}$ and $200$ eV $Kr^{6+}$ capturing one electron from He.
2. Experimental technique and data treatment

The apparatus SINE used in the present investigation has been described in detail previously (1). The projectiles are produced as recoil ions and after acceleration and focusing they enter a magnet for charge and momentum analysis. The collision cell is at a floating potential which determines the collision energy. After passing through the collision cell the ions are charge and energy dispersed by an electrostatic hemispherical analyzer and detected by a ceramic channel electron multiplier. An energy-gain spectrum of the charge-changed particles is obtained by sweeping the retardation voltage. In order to obtain total cross sections the retarding voltage is programmed to scan the primary beam before each scan of the charge-changed component. A Faraday cup collects the primary beam, and the total charge is integrated to normalize the counting time for each data point.

3. Results and discussion

For the collision systems considered in this investigation, angular scattering effects can not be neglected. These will influence the energy-gain spectra mainly in that peaks will be shifted and become asymmetric, some actually having most of their intensity in a characteristic low-energy-gain shoulder. This effect has been studied in model form by Andersson et al (6), who used a semiclassical framework. Recently Hansen and Taulbjerg (8) performed a close-coupling calculation using a 26-state atomic basis expansion in the impact parameter formulation to study similar effects. For practical reasons we here follow the approach of Ref. 6 to generate theoretical energy gain spectra. These are useful in assigning active reaction channels and to some extent necessary to interpret partial cross sections correctly for close-lying channels.

3.1 O$^{2+}$ + He

Fig. 1 shows an energy-gain spectrum of O$^{2+}$ single-electron capture from He at 300 eV impact energy. The O$^{2+}$-He collision system is relatively simple in that only two final reaction channels seem to be active at low energies. The proposed reactions are

$$\text{O}^{2+}(2p^2 \ 3P) + \text{He} = \text{O}^{+*}(2p^3 \ 2P^0) + \text{He}^+ + 5.54\text{eV} \quad (1)$$

$$\text{O}^{2+}(2p^2 \ 3P) + \text{He} = \text{O}^{+*}(2p^3 \ 3D^0) + \text{He}^+ + 7.24\text{eV} \quad (2)$$

The energy defects $Q$ of these reactions, 5.54 and 7.24 eV, respectively, are higher than the observed energy gains $\Delta E$ because of the sharing of the released energy between projectile and target. The shift of the peaks in Fig. 1 can be explained by the large projectile to target mass ratio combined with the angular scattering experienced by the projectile (8).

The O$^{2+}$-He system has recently been studied both by translational energy-gain and by angular differential measurements in the low-energy regime by Kamber et al (9). Their energy-gain spectrum at 80 eV impact energy shows contributions only for population of the $2P^0$ term of O$^+$. The differential cross section shows an oscillatory behaviour as a function of the scattering angle and this is interpreted in Ref. 9 as an interference oscillation. We note here that a very similar oscillation appears in the differential cross sections calculated by Andersson et al (6), even though their method has averaged out all interference effects.
To investigate this point we have first calculated an energy-gain spectrum using the method of Ref. 6 which is shown in Fig. 2. For this calculation we have, following Butler et al.\(^{(10)}\), Bienstock et al.\(^{(11)}\) and Heil and Sharma\(^{(12)}\), assumed that only the quasimolecular II states formed in the initial channel are active in the electron transfer process. The potentials used have been of the kind described by Andersson et al.\(^{(6)}\), and the initial diabatic potential has been assumed to become repulsive at a crossing distance of 2.58 a\(_0\). The diabatic coupling elements have been varied to give reasonably good resemblance between experiment and theory.

Fig. 1: Energy-gain spectrum for 300 eV O\(^{2+}\) capturing one electron from He.

Fig. 2: Theoretical energy-gain spectrum for 300 eV O\(^{2+}\) capturing one electron from He.
Using the same parameters the angular differential cross section has been calculated and is shown in Fig. 3. The main part of the total structure derives primarily from the $^2P^0$ reaction channel. The shape can be explained in terms of a deflection function and a rainbow phenomenon, as described in Ref. 6. By comparison with the cross section measured by Kamber et al (9) at 247 eV one can see the similarity for the first two "undulations", but the experimental cross section shows an additional third peak at somewhat larger angles. The interpretation of this third peak is still unknown, but we note that there are additional reaction channels in this collision system that might become active only at small enough impact parameters (13).

![Figure 3](image_url)

**Fig. 3**: Theoretical angular differential cross section for 300 eV $O^{2+}$ capturing one electron from He.

### 3.2 Kr$^{6+}$ + He

The identification of active channels in the Kr$^{6+}$+He system is somewhat uncertain because of the lack of spectroscopic information on the excited states of Kr$^{5+}$. To get Q-values which are useful for our collision model we have therefore used the calculated excitation energies for the $4s^24d~^2D$ and $4s^25s~^2S$ levels from Aashamar et al (14), and for the $4s^25p~^2P^0$ level from Fraga et al (15). The experimental energy-gain spectra in Fig. 4a-c suggest two dominant channels in the relevant energy range. The 5s and 5p channels are strong candidates for the two active channels, and calculations were performed with these two channels open and the 4d channel closed. The diabatic coupling element was chosen as given by Taulbjerg (16). The experimental spectra are fairly well reproduced by the calculations, Fig. 4d-f, which supports the identification of the active channels.
Fig. 4: Energy-gain spectra for single-electron capture by Kr$^{6+}$ from He. a-c: Experimental spectra at 200, 500 and 2000 eV impact energy, respectively. d-f: Corresponding theoretical spectra.

A characteristic feature of this system is the change of the relative intensity distribution between the channels as the energy is varied. The outer channel (5p) becomes more adiabatic at the lower energy and takes a greater part of the probability flux at the expense of the inner channel (5s). This is clearly reproduced by the calculations. According to the theoretical model, the shoulder extending to lower energy gains mainly emanates from the 5s channel.

In fig. 5 we present the angular differential cross section at 200 eV impact energy. It presents a large peak with a structure on top. A closer analysis of the structure shows

Fig. 5: Theoretical angular differential cross section for 200 eV Kr$^{6+}$ capturing one electron from He.
that the small-angle part results from rainbow scattering in the channel leading to 5p, while the part at larger angles mainly reflects the low-energy gain shoulder present in Fig. 4d. Since also this cross section gives the impression of showing interference oscillations, some care must be exercised in interpreting these angular scattering distributions.

References