Measurement of the Charge Exchange Cross Section for \(N^7+\), \(O^7+\) Ions in Collision with Atomic \(H\)

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Abstract

The absolute total cross sections for the charge exchange between highly charged ions \(15N^7+\), \(O^7+\), and atomic \(H\) have been measured with the ion-atom merged-beams apparatus at Oak Ridge National Laboratory. The collision energy range is from 1224 down to 2 eV \(u^{-1}\), which covers outflowing hot components of astrophysical charge exchange plasmas like stellar-wind and supernova remnants. Good agreement with the previous measurements and theory is found for the collision energies above 100 eV \(u^{-1}\), while below 100 eV \(u^{-1}\) limited agreement is achieved with the available calculations. These cross-section data are useful for modeling X-ray emission resulting from the charge exchange at the interface of hot plasma interacting with ambient neutral gas.

Unified Astronomy Thesaurus concepts: Atomic physics (2063); Collision processes (2065); Atomic data benchmarking (2064); Charge exchange recombination (2062)

1. Introduction

Charge exchange (CX) has been established to be a primary physical source of the soft X-ray background in various astrophysical environments, such as the interfaces where the solar wind ions interact with neutrals in comets and planetary atmospheres (Lisse et al. 1996; Cravens 1997; Dennerl et al. 1997; Beiersdorfer et al. 2003; Dennerl et al. 2006; Branduardi-Raymont et al. 2007; Hui et al. 2009; Gu et al. 2016). It is also a potentially important mechanism for X-ray emission from the North Polar Spur region (Lallement 2009), supernova remnants (Katsuda et al. 2011), around star-forming galaxies (Liu et al. 2012), and in clusters of galaxies (Fabian et al. 2011; Aharonian et al. 2016). Therefore, modeling CX emission is crucial for interpreting astrophysical observations and CX plasma diagnostics (Dennerl et al. 2006; Smith et al. 2014).

In modeling, the total cross section (TCS) of CX is important for deriving the ionization concentration of CX plasmas, and for calculating total X-ray luminosity, which is one of the morphology observations that can account for the physical mechanism of emission. Cravens (1997) developed a CX model with ions that produced X-rays observed by ROSAT and by adopting the CX cross section of \(3 \times 10^{-15}\) cm\(^2\) for all the neutral considered. The total calculated extreme-ultraviolet/X-ray luminosity for comet Hyakutake only agrees with the observed luminosity of \(4 \times 10^{15}\) ergs \(s^{-1}\) within a factor of 2. H"aberli et al. (1997) extended the CX model by investigating spectra lines from C, O, and Ne ions: The TCS of C, O ions were for measurements for collision with \(H_2\) (Phaneuf et al. 1982). The TCS of the Ne ion was assumed to be \(4 \times 10^{-15}\) cm\(^2\). The X-ray luminosity from this calculation was \(2.7 \times 10^{16}\) ergs \(s^{-1}\), a factor of 10 larger than the observation.

Wegmann et al. (1998) used a classical over-the-barrier model to calculate TCS of CX and the estimated luminosity was \(1.2 \times 10^{16}\) ergs \(s^{-1}\), six times larger than the observation. These examples manifest that the uncertainties of TCS data of CX significantly impact the accuracy of calculations of total X-ray luminosity.

Of the neutral constituents, atomic \(H\) is the main interstellar neutral species (Qu"emerais et al. 2000; Bodewits et al. 2007; Mullen et al. 2017; Kunz 2019). The existing TCS data of CX between highly charged ions and \(H\) atoms are mainly reported at or above keV \(u^{-1}\) energies (Panov et al. 1993; Bendahan et al. 1985; Dijkkamp et al. 1985). These measurements seldom go lower in energy due to the technical challenges of measuring with atomic \(H\). Alternatively, the merged-beams technique can not only provide the ground-state atomic \(H\) target, but also measure CX covering several orders of magnitude in collision energy.

2. Merged-beams Technique

The concept of using merged beams to measure interactions at low relative energies has been discussed in the literature (Phaneuf et al. 1999). When two beams intersect, the relative collision energy in the center-of-mass frame is given by

\[
E_{rel} = \frac{E_1}{m_1} + \frac{E_2}{m_2} - 2 \frac{E_1 E_2}{m_1 m_2} \cos(\theta),
\]

where \(m_i\), \(E_i\) denotes the mass and initial energy of each beam, and \(\theta\) denotes the intersection angle between the two beams’ reactions. Figure 1 shows a schematic view of the merged-beams apparatus at Oak Ridge National Laboratory (ORNL). With this apparatus, CX reaction can be measured from thermal to several keV \(u^{-1}\) energy range. More details can be found elsewhere (Havener et al. 1989; Pieksma et al. 1996; Pieksma & Havener 1998).
Taking $^{15}\text{N}^7\text{+} - \text{H}$ measurements as an example, $^{15}\text{N}^7\text{+}$ ions were extracted from an electron cyclotron resonance ion source with the intensity around 1.0 $\mu$A on a high voltage platform, the momentum analyzed by a 90° dipole magnet, and then accelerated off the high voltage platform to the desired energies. The $^{15}\text{N}^7\text{+}$ isotope was magnetically dispersed from a nearby large $\frac{m}{q} = 2$ contaminant ($m$, $q$ are the mass and charge state of the ions, respectively). Several sets of electrostatic quadruple lenses, electrostatic steerers, and adjustable slits were used to optimize the $^{15}\text{N}^7\text{+}$ beam before entering into the merge-path. An atomic H beam was obtained through photodetachment of an H$^-$ beam. A 19.9 keV H$^-$ beam was extracted from a duoplasmatron ion source, the momentum analyzed by a 30° dipole magnet, and then photodetached using the inner cavity of a 1.06 $\mu$m Nd:YAG laser (Havener et al. 1989). The intensity of the H beam was typically 40 nA with low divergence as measured by beam profile monitors and only a few millimeters in diameter. CX reaction occurs in the merge-path distance of 32.5 cm.

During the measurement, the vacuum in the merge-path was in the range of 10$^{-10}$ Torr. An ionizer with an electric field strength of 30 kV cm$^{-1}$ was used to minimize the contamination from Rydberg H, which was produced through stripping collisions between the H$^-$ beam and residual gases. The fraction of beam–beam signal from excited H atoms was measured with the laser off, which led to a less than 5% correction to the ground-state cross section. At the post-merge path, $^{15}\text{N}^7\text{+}$, $^{15}\text{N}^6\text{+}$, and the signal H$^+$ ions are magnetically separated in the plane of horizontal dispersion; $^{15}\text{N}^7\text{+}$ and $^{15}\text{N}^6\text{+}$ ions were collected in the same Faraday cup. The signal H$^+$ ions were directed into a channel electron multiplier (CEM) detector, which was mounted vertically out of the dispersion plane to reduce background from the $^{15}\text{N}^7\text{+}$ beam. In front of the CEM detector, an electrostatic steerer and a lens were used as a diagnostic to ensure a complete collection of the signal H$^+$ ions.

3. Cross-section Measurement

For the merged-beams technique, CX cross sections are determined by measuring the rate of H$^+$ product ions produced by the beam–beam interaction over the merge length L. The cross-section value is calculated at each velocity from the directly measurable quantities through the equation

$$\sigma = \frac{R}{\epsilon} \frac{\gamma q e^2 v_1 v_2}{v_r L F},$$

where R, I$_1$, and I$_2$ correspond to the measured signal count rate, and effective current produced by neutral H and N$^7+$ current, respectively. The true signal rate is given by R/\epsilon, \epsilon being the efficiency of the CEM for detecting H$^+$ at velocity v$_1$, and the true neutral “current” is I$_1$/\gamma, \gamma being the measured effective secondary-electron emission coefficient for the neutral particle. The quantity q is the charge state of the ion, e is the electric charge, and v$_r$ is the relative velocity of the two beams; $\langle F \rangle$ is the effective form factor determined by measuring the spatial overlap of the two beams along the merge-path L.

Rigorously, $\langle F \rangle$ is determined by integrating the product of the number densities of the two beams at every point along the merged path. Here the beam–beam overlap is measured at four different locations—z$_j$ along the merge-path; details can be found in the reference of Havener et al. (1989). At each position, the beam-profile monitors perform two orthogonal one-dimensional scans of each beam, giving I$_j$ at z = z$_j$.

$$I_i(y) = \int n_i(x, y, z = z_j)n_2(x, y, z)dx,$$

$$I_i(x) = \int n_i(x, y, z = z_j)n_2(x, y, z)dy,$$

$$\langle F(z_j) \rangle = \frac{\int I_i(y)I_2(y)dy \int I_1(x)I_2(x)dx}{\int I_i(y)dy \int I_1(x)dx \int I_2(y)dy \int I_2(x)dx},$$

By extrapolating and interpolating values for $\langle F(z_j) \rangle$ along the merge-path, an averaged value of $\langle F \rangle$ can be calculated.
The measured TCS for $^{15}$N$^+$, O$^+$ CX with H

| Collision Energy | TCS (10^{-16} cm²) | Relative Error | Total Error |
|------------------|---------------------|----------------|-------------|
| 10.0             | 32.4                | 7.1            | 15.8\(^a\) |
| 20.8             | 37.5                | 6.0            | 14.4\(^a\) |
| 40.7             | 35.9                | 4.4            | 5.8         |
| 61.6             | 40.6                | 4.0            | 5.8         |
| 101.3            | 49.2                | 3.6            | 6.2         |
| 149.0            | 54.9                | 5.4            | 7.8         |
| 202.3            | 50.3                | 3.5            | 6.3         |
| 302.0            | 48.3                | 3.4            | 6.0         |
| 422.8            | 47.0                | 3.3            | 5.9         |
| 501.5            | 46.7                | 4.3            | 6.5         |
| 603.0            | 50.3                | 2.9            | 6.0         |
| 700.0            | 48.1                | 3.7            | 6.2         |
| 900.9            | 44.5                | 3.4            | 5.8         |
| 1197.0           | 48.9                | 4.8            | 7.0         |

Note. The collision energies are in units of eV u⁻¹, TCS, relative (statistical) error, and total error are in units of 10⁻¹⁶ cm². Relative and total errors are listed below and corresponding to a 90% confidence level.

\(^a\) The error bar of these two measurements are doubled, due to limited diagnostics on the signals collected.

4. Results and Discussion

The measured TCS for CX between $^{15}$N$^+$, O$^+$, and H are listed in Table 1, along with the relative and total errors at a 90% confidence level. The total error is a quadrature sum of the relative and systematic errors.

In Figure 2(a), we show the present measurements of $^{15}$N$^+$ –H with total errors as well as the available theoretical calculations and measurements. Clearly, the present measurements agree well with the measurements by Meyer et al. (1985), both show a broad plateau behavior in the energy range from 100 to 1200 eV u⁻¹. The TCS value is around $5 \times 10^{-15}$ cm², which is approximately 30% smaller than $7 \times 10^{-15}$ cm² estimated by the $q \times 10^{-15}$ cm² scaling law (Phaneuf 1983). The present measurements show an excellent agreement with atomic orbital close coupling (AOCC; Fritsch & Lin 1984) and molecular orbital close coupling (MOCC) calculations (Kimura 1986). The TCS results measured by Panov et al. (1983) are less than $2.7 \times 10^{-15}$ cm² for the collision energy above 500 eV u⁻¹. Above 100 eV u⁻¹, the multichannel Landau–Zener (MCLZ) calculations, obtained from the Kronos CX database (Mullen et al. 2016, 2017), are slightly lower than the measured values. The multichannel Landau–Zener theory with rotational coupling included (MLZRC; Janev et al. 1983) shows some limited agreement with the present measurement.

Below 100 eV u⁻¹, the measured TCS shows a decreasing tendency, which seems to be suggested by both AOCC and MOCC calculations. The present measurements are significantly lower than the MCLZ calculations from the Kronos.
database, and only show fair agreement with the prediction of N\(^{2+}\) – D using a coupled channel molecular orbital hidden crossing calculation (CCMOHC; Thompson et al. 2000). Qualitatively, the decrease in the TCS can be explained from the reaction window theory. The avoided crossing of the principal quantum number n = 5 capture is estimated to be around 12 atomic units for CX in 10 keV u \(^{-1}\) –0.1 keV u \(^{-1}\) N\(^{2+}\) collision with H where the crossing distance is within the reaction window (Kimura 1986). With the velocity decreasing, the reaction window narrows and shifts to larger nuclear distances (Taulbjerg 1986) with no nearby crossings in the potential curve. This leads to the decreasing cross section toward few eV u \(^{-1}\) energies. Experimental data below 10 eV u \(^{-1}\) are required to benchmark the decreasing cross section predicted by the CCMOHC theory.

Figure 2(b) shows that the present measured TCS of O\(^{2+}\) CX with H is also consistent with the existing measurements by Meyer et al. (1985). The TCS values measured by Panov et al. (1983) are below 3.0 × 10\(^{-15}\) for the collision energy above 438 eV u \(^{-1}\). The MCLZ calculation from the Kronos database for CX between O\(^{2+}\) and H significantly underestimates the measurements for the energies above 100 eV u \(^{-1}\), while it overestimates the TCS values below 100 eV u \(^{-1}\). For the low energy CX, the collision velocity is lower than the orbital velocity of the active electron, and electronic motion adiabatically adjusts to the nuclei motion of the collision partners (Bransden & McDowell 1992). Insufficient treatment of complicated dynamical effects can lead to great uncertainty in MCLZ calculations. The fitted results by Janev et al. (1995) also overestimate TCS below 100 eV u \(^{-1}\).

In Figure 3, a comparison of the present measurements of the fully stripped \(^{15}\text{N}^{7+}\) and O\(^{2+}\) with a single electron on the core is presented. It has been pointed out that the projectile core effects become of increasing influence for multielectron ions as the collision energies go down (Harel & Jouin 1988; Beijers et al. 1992; Zhao et al. 2007). Indeed, previous merged-beam measurements for 4+ ions on H show a strong core effect below 1 keV u \(^{-1}\) (Folkerts et al. 1995; Pieksma et al. 1996; Blik et al. 1997; Havener et al. 2005). Since both measurements presented here agree with the previous measurements of Meyer et al. (1985) at higher energies, only relative errors are shown here to better illustrate any possible core effects. The present measurements suggest that the projectile core effects are negligible compared to our error bars for the ions considered here. Note that there is an upturn below 10 eV u \(^{-1}\) for O\(^{2+}\) – H, deviating from the 100 to 10 eV u \(^{-1}\) trend. This may be attributed to trajectory effects due to an attractive ion-induced dipole (Pieksma et al. 1996).  

5. Conclusion

The absolute TCS data of CX between \(^{15}\text{N}^{7+}\), O\(^{2+}\), and H are measured for the collision energy range from 1224 eV u \(^{-1}\) to 2 eV u \(^{-1}\). The present measurements are in excellent agreement with the previous measurements of Meyer et al. (1985) and agree with close coupling calculations for the collision energy above 100 eV u \(^{-1}\). Whereas for the energy below 100 eV u \(^{-1}\), significant disagreements exist between the measurements and MCLZ calculated results from the Kronos database. This suggests that dynamical coupling effects need to be sufficiently treated in MCLZ calculations for these ions. The measurements do not show any significant projectile core effects on the TCS of CX processes toward eV u \(^{-1}\) energies for the present isocharged ions. Considering the sensitivity of TCS data on the luminosity of astrophysical X-ray induced by CX, further theoretical calculations as well as more laboratory measurements are required.

The merged-beams apparatus has been modified for high-resolution X-ray spectrum measurements. TCS data and associated X-ray line ratios of astrophysical interest can be measured for an energy range from few eV u \(^{-1}\) to 1000 eV u \(^{-1}\). These data will be helpful for accurately modeling the astrophyssical CX X-ray induced by hot outflows for the next generation mission observations (Inoue et al. 2019).

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