Published in final edited form as:

Phys Rev A. 2013 November ; 88(5): . doi:10.1103/PhysRevA.88.052702.

X-ray Emission Measurements following Charge Exchange Between C^{6+} and He

X. Defay,

Department of Physics, University of Wisconsin, Madison, WI 53706

K. Morgan,

Department of Physics, University of Wisconsin, Madison, WI 53706

D. McCammon,

Department of Physics, University of Wisconsin, Madison, WI 53706

D. Wulf,

Department of Physics, University of Wisconsin, Madison, WI 53706

V. M. Andrianarijaona,

Department of Physics, Pacific Union College, Angwin, CA 94508

M. Fogle,

Department of Physics, Auburn University, Auburn, AL 36849

D. G. Seely,

Department of Physics, Albion College, Albion, MI 49224

I. N. Dragani ,

Oak Ridge National Laboratory, Oak Ridge TN 37831-6372

C. C. Havener

Oak Ridge National Laboratory, Oak Ridge TN 37831-6372

Abstract

X-ray spectra following charge exchange collisions between C^{6+} and He are presented for collision energies between 460 eV/u and 32,000 eV/u. Spectra were obtained at the Oak Ridge National Laboratory Multicharged Ion Research Facility using a microcalorimeter X-ray detector capable of fully resolving the C VI Lyman series lines through Ly- γ . These line ratios are sensitive to the initial electron I -distribution and test our understanding of the charge exchange process. In addition, these line ratios are important for identifying charge exchange in astrophysical contexts involving the interaction of solar wind ions with neutrals. Our measurements are performed at collision velocities (300 km/s to 2500 km/s) which overlap most of the solar wind range. Additional data of this type can be combined with computations to provide an extensive set of reliable line ratios and absolute cross sections for the interpretation of a variety of astrophysical situations.

I. INTRODUCTION

Charge Exchange (CX) between highly charged ions and neutral atoms or molecules results in an electron(s) from the neutral being captured into an excited state of the resulting ion with a range of n and l values. The total cross sections are typically large ($\sim 10^{-15}$ cm²) and therefore important in many environments where both ions and neutrals are present. Charge exchange is important in magnetic fusion studies to model, e.g., penetration and energy deposition of neutral beams [1] and for the interpretation of X-ray diagnostics [2].

With the discovery of highly charged ions in the solar wind [3, 4] interacting with comets, planets, and interstellar neutrals in the heliosphere, there has been renewed interest in accurate charge exchange data in the astrophysics community as well. The X-rays that result from the de-excitation of the ions following CX are important in these astrophysical contexts. For example, the best calculations of the interactions between solar wind ions and neutral hydrogen and helium in interplanetary space indicate that it could be responsible for essentially all of the observed 100–300 eV diffuse X-ray background [5, 6]. This radiation was previously thought to arise from collisional excitation in 10^6 K interstellar gas and there are observational arguments that it is not entirely dominated by CX. Observationally disentangling these processes is subtle since thermal emission at these temperatures is primarily in the same atomic lines as those produced in the radiative cascades following CX. The different excitation mechanisms will produce different line ratios, but accurate predictions are needed for the expected ratios from CX.

Predicting CX spectra requires knowledge of the angular momentum distribution of the electron following the capture, in addition to its n -level. These state-selective partial cross sections are highly dependent on collision velocity over the range of astrophysical interest, and thus several models are available for different velocity regimes. At collision energies above the peak in the cross section where the collision velocity matches the orbital velocity of the captured electron, Classical Trajectory Monte Carlo (CTMC) calculations (e.g., Ref. [7]) have been successful. At the peak, the Classical over the Barrier Model (CBM) [8] predicts the total cross section and n -level for the capture process, and has been extended to estimate the velocity-dependent average angular momentum [9]. At velocities below the peak in the cross section, many states are active in the electron capture process and Atomic-Orbital or Molecular-Orbital Close-Coupling methods (AOCC and MOCC) are required [10, 11]. AOCC and MOCC calculations are difficult to perform and are not generally available for more complicated, multi-electron systems, so they have not been used extensively in astrophysical modeling of CX. In some cases, approximate methods like Multi-Channel Landau-Zener (MCLZ) can be used with some success [12]. Laboratory measurements capable of resolving CX line emission spectra serve to verify and provide guidance for these models. Previous X-ray measurements of CX emission relevant to the Solar Wind have been performed mainly by three experimental groups, the Chutjian group at the Jet Propulsion Laboratory [13, 14] using a solid state germanium detector with a resolution of only about 100 eV, the Beiersdorfer group at Lawrence Livermore National Laboratory using their electron beam ion trap [15, 16] with a solid state and a microcalorimeter detector but restricted to low collision energies (less than 20 eV/u), and the Hoekstra group [17, 18] using a variety of spectrometers measuring in the soft X-ray bandpass 0.02–0.25 keV.

We report here the results of X-ray emission measurements made at the Oak Ridge National Laboratory (ORNL) Multicharged Ion Research Facility[19] (MIRF) for CX between fully stripped carbon ions and neutral helium (resulting in hydrogen-like carbon) with relative velocities overlapping most of the solar wind range. Charge exchange with carbon ions has been identified as important in both magnetic fusion plasma devices and astrophysical contexts involving the interaction of solar wind ions with neutrals. Moreover, the Lyman series lines of C VI are bright and can be reasonably well isolated with current astrophysical instrumentation, so data exist for some line ratios. Charge exchange of C^{6+} on He has also been addressed by existing theoretical work, allowing comparison with our measurements. The aim of this experiment is to directly measure X-ray emission line ratios of CX spectra as a function of collision velocity and compare them with predictions made by current models.

II. CHARGE EXCHANGE AND X-RAY EMISSION

In the process of charge exchange, an electron(s) is transferred to an n, l state of the ion when the electron overcomes the barrier between the neutral and the ion. Using the Classical over the Barrier Model (CBM) for He and C^{6+} , capture occurs mainly into $n=3$ [8, 9]. The captured electron will transition from the $n=3$ shell to the ground state via the emission of one or more photons.

The total cross section ($\sim 1.5 \times 10^{-15} \text{ cm}^2$) is predicted to be only weakly dependent on relative velocities above 625 km/s (characteristic of fast solar wind), with a decreasing cross section toward lower velocities (slow solar wind) [10]. However, the partial cross sections for different initial angular momentum states tend to vary more significantly over all velocities. These differences in the initial l -distribution affect the radiative cascade and cause the observed line ratios to be velocity dependent. For example, electrons captured into a p -state ($l=1$) are able to de-excite directly into the ground state from the $n=3$ or $n=4$ energy level, resulting in Ly- β or Ly- γ , respectively. The different transitions of C VI are summarized in the Table I. Note that the last two transitions in the table remove a fraction of the $3p$ or $4p$ population to a metastable state which is not observed. For electrons captured into a higher or lower l -value, de-excitation directly into the ground state is forbidden by selection rules for electric dipole radiation ($l = \pm 1$).

III. EXPERIMENT

The experiment was conducted on the ORNL ion-atom merged-beams apparatus (see e.g., Ref [20]), using the microcalorimeter X-ray detector from a University of Wisconsin/Goddard Space Flight Center sounding rocket experiment [21]. An all-permanent magnet Electron Cyclotron Resonance (ECR) ion source on a high voltage platform [20] produced highly charged $m=13$ carbon ions which were momentum analyzed by a dipole magnet to produce an uncontaminated C^{6+} beam. Using both acceleration and deceleration off the platform, the C^{6+} energy ranged from 462 eV/u to 32,300 eV/u which corresponds to

velocities from 300 km/s to 2500 km/s. The X-ray detector viewed a 2 cm section of the beam line, where He gas was introduced as a target. These gas cell measurements could be performed as the merged-beams X-ray measurements with H is still under development.

Figure 1 shows the calorimeter mounted above the beam line to detect prompt X-rays emitted 90° from the beam direction. X-ray emission has been assumed to be isotropic and possible angular dependence with respect to the beam axis has not been taken into account. This is a reasonable assumption given that we are comparing ratios and that the $n=2$ shell (which leads to Ly- α radiation) is populated by cascades from higher levels [22]. The $1\text{ cm} \times 1.2\text{ cm}$ detector was positioned 23 cm away from the beam line, with a solid angle of $2.3 \times 10^{-3}\text{ sr}$ for X-rays emitted from the viewed portion of the beam. For typical 20 nA ion beams, the He gas pressure was adjusted to provide an optimum count rate ($\sim 0.5\text{ Hz}$ on each of 36 pixels), which was $\sim 1 \times 10^{-3}\text{ Pa}$ (10^{-5} Torr). These detectors have an energy resolution of better than 10 eV FWHM at 400 eV (taking into account the microphonics and electromagnetic noise of the lab environment), which is sufficient to fully resolve C VI Ly- α through Ly- γ . A representative spectrum is shown in Fig. 2.

The relative intensities of the different lines were measured by fitting the peaks in each spectrum with a functional form that accurately represents the shape of the peaks. The low energy tails seen on the peaks in Fig. 2 seem to be caused by pile-up in the detector since the size of the tail relative to the size of the central peak was observed to be directly correlated with the count rate. The X-ray transmission of the thin aluminum filters used to shield the detector array from infrared radiation is energy dependent. The measured intensities are corrected for this transmission. The net detection efficiencies for the Ly- α , Ly- β , and Ly- γ lines are 0.065, 0.124, and 0.153 respectively.

IV. RESULTS AND DISCUSSION

The integrated ratios of Ly- β and Ly- γ to Ly- α as a function of collision velocity are shown in Figures 3 and 4. Error bars are 2σ and include both statistical uncertainty and systematic uncertainty arising from variations in the shape of the peaks. Values used by D. Koutroumpa in her solar wind models are also included (Koutroumpa 2007, references cross sections from V. Kharchenko, private communication). The estimated cross sections assume primary capture into the $n=4$ shell (more appropriate for an H rather than a He target), with a statistical L -distribution at high velocities (fast solar wind [700 km/s]) and a distribution centered at $L=1$ for low velocities (slow solar wind [400km/s]) [23]. The cross section values used in the solar wind model do not show good agreement with the measured line-ratios, particularly for γ/α . However, for the highest velocities ($>2000\text{ km/s}$) we do observe a β/α ratio that is consistent with a statistical L -distribution for capture into the $n=3$ shell (not shown) and increasing β/α ratios at lower velocities indicate increasing capture into the $L=1$ state.

The line ratios predicted by AOCC[10] show good agreement with the data for velocities above 1500 km/s. At the lowest velocities (500 km/s), however, the AOCC predictions show an increasing $3/\alpha$ ratio while the observed ratio drops sharply. For these velocities, the collision complex is better described by molecular states. MOCC calculations [11] show

increased capture into the $3d$ state (not the $3p$ state) at lower velocities, decreasing the β/a ratio in qualitative agreement with observations. The MOCC calculations predict no significant capture into the $n=4$ shell, resulting in negligible γ/a ratios. Both the AOCC and MOCC predictions presented here assume straight line trajectories which are only valid at higher velocities near the peak in the cross section. Fully quantal MOCC calculations (e.g., Ref [24]) do not make this assumption.

Our results can be compared to Vacuum Ultraviolet (VUV or soft X-ray) emission measurements[18] for C^{6+} on He. The l degenerate n -shell emission cross sections for the Balmer transitions Ba- α ($n=3-2$) and Ba- β ($n=4-2$) were measured down to 250 km/sec, slightly lower in velocity than our measurements. The emission data joined smoothly with previous higher velocity measurements (up to 1100 km/sec) from the same group[25]. Neglecting cascades from the $n=4$ shell, the 3-2 transition is most sensitive to the $3d$ cross section. In contrast to what we conclude, at low velocities the AO model[10] is found to better represent the data than the MO model[11]. Both models, however, predict 3-2 emission cross sections that are larger than that observed over the entire energy range. Our measurements Ly- β to Ly- α ($3-1/2-1$) correspond to a ratio which, neglecting cascades from $n=4$ and assuming the $3s$ contribution is small, is most sensitive to $3p/3d$. The ratio eliminates uncertainty related to target density which in the VUV measurements corresponds to a beam-beam overlap.

V. CONCLUSIONS

Emission spectra from CX are dependent on the initial distribution of angular momentum states of the captured electron, which is strongly dependent on the collision velocity. These direct measurements of Lyman line ratios for C^{6+} on He over the astrophysically interesting range illustrate the difficulty of precise calculations even for this relatively simple system. AOCC calculations show good agreement with the measured ratios above 1500 km/s, but only the more difficult MOCC calculations reproduce the observed trend at the lowest velocities. More modern MOCC calculations which are not restricted to straight line trajectories can be benchmarked by our Lyman line ratios and the previous VUV emission cross sections. The simple model used by Koutrompa produces cross sections for a large number of more complex ions, but shows poor agreement with the C+ on He data. Validation of CX models in various velocity ranges will allow more accurate predictions of CX spectra, enabling an improved understanding of the contribution of charge exchange in astrophysical contexts.

ACKNOWLEDGMENTS

This research is supported in part by the NASA Solar & Heliospheric Physics Program NNX07ZDA001N, NASA grant NNX09AF09G, and by the Office of Fusion Energy Sciences and the Office of Basic Energy Sciences of the US Department of Energy. VA is supported by the National Science Foundation through Grant No. PHY-106887. Special thanks goes to the summer students C. I. Guillen, S.L. Romano, and A. K. Vasantachart from Pacific Union College, CA, F. Salces Carcoba from the Universidad Autonoma de San Luis Potosi, Mexico and from D. J. Nader from Universidad Veracruzana, Xalapa, Mexico.

References

- [1]. Hulse RA, Post DE, and Mikkelsen DR, J. Phys. B 13, 3895 (1980).
- [2]. Isler RC, Plasma Phys. Control. Fusion 36, 171 (1994).
- [3]. Lisse CM, Science 274, 205 (1996).
- [4]. Cravens TE, Geophys. Res. Lett. 24, 105 (1997).
- [5]. Lallement R, AA 418, 143 (2004).
- [6]. Koutroumpa D, Lallement R, Raymond JC, and Kharchenko V, Astr. J. 696, 1517 (2009).
- [7]. Simcic J, Schultz DR, Mawhorter RJ, Cadez I, Greenwood JB, Chutjian A, Liesse CM, and Smith SJ, Phys. Rev. A 81, 062715 (2010).
- [8]. Ryufuku H, Sasaki K, and Watanabe T, Phys. Rev. A 21, 745 (1980).
- [9]. Burgdorfer J, Morgenstern R, and Niehaus A, J. Phys. B: At. Mol. Phys. 19, L507 (1986).
- [10]. Fritsch W and Lin CD, J. Phys. B: At. Mol. Phys. 19, 2683 (1986).
- [11]. Kimura M and Olson RE, J. Phys. B: At. Mol. Phys. 17, L713 (1984).
- [12]. Havener CC, Rejoub R, Vane CR, Krause HF, Savin DW, Schnell M, Wang JG, and Stancil PC, Phys. Rev. A 71, 034702 (2005).
- [13]. Greenwood JB, Chutjian A, and Smith SJ, ApJ 529, 605 (2000).
- [14]. Greenwood JB, Williams ID, Smith SJ, and Chutjian A, ApJ 533 (2000).
- [15]. Beiersdorfer P, Lisse CM, Olson RE, Brown GV, and Chen H, ApJ 549 (2001).
- [16]. Beiersdorfer P, ARA&A 41 (2003).
- [17]. D. Bodewits, Z. Juhasz, and R. Hoekstra, 606 (2004).
- [18]. Beijers RHJPM, Schlatmann AR, Morgenstern R, and de Heer FJ, J. Phys. B: At. Mol. Opt. Phys. 25, 463 (1992).
- [19]. Meyer FW, Bannister ME, Dowling D, Hale JW, Havener CC, Johnson JW, Juras RC, Krause HF, Mendez AJ, Sinclair J, Tatum A, Vane CR, Musafiri EB, Fogle M, Rejoub R, Vergara L, Hitz D, Delaunay M, Girard A, Guillemet L, and Chartier J, Nucl. Instr. and Meth. in Phys. Res. B 242, 71 (2006).
- [20]. Dragani IN, Seely DG, and Havener CC, Phys. Rev. A 83, 054701 (2011).
- [21]. McCammon D, Barger K, Brandl DE, Brekosky RP, Crowder SG, Gygas JD, Kelley RL, Kilbourne CA, Lindeman MA, Porter FS, Rocks LE, and Szymkowiak AE, J Low Temp Phys 151, 715 (2008).
- [22]. Greenwood JB, Williams ID, Smith SJ, and Chutjian A, Phys. Rev. A 63, 062707 (2001).
- [23]. Koutroumpa D, Thesis, l'Universite Pierre et Marie Curie Verrieres-le-Buisson (2007).
- [24]. Nolte JL, Stancil PC, Liebermann HP, Buenker RJ, Hui Y, and Schultz DR, J. Phys. B 45, 245202 (2012).
- [25]. Dijkkamp D, Gordeev YS, Brazuk A, Drentje AG, and de Heer RJ, J. Phys. B: At. Mol. Phys. 18, 737 (1985).

FIG. 1.
(color online) Detectors operate at 50 mK and are positioned 23 cm above the beam line,
viewing 2 cm of the C^{6+} beam in $\sim 1 \times 10^{-3}$ Pa of He gas.

FIG. 2.

(color online) X-ray spectrum from C^{6+} on He at 364 km/s (not corrected for filter transmission). The Ly- α , Ly- β , and Ly- γ lines are clearly resolved with an average resolution better than 10 eV FWHM. Fits are shown for individual lines as well as the total (sum) fit.

FIG. 3.

Ratio of Ly- β to Ly- α for collision velocities between 300 km/s and 2500 km/s. Current data represented by open circles with 2σ error bars. Theoretical values used by D. Koutroumpa in her solar wind models are also shown [23], along with AOCC [10] and MOCC [11] predictions. Only MOCC calculations show the correct trend at the lowest velocities.

FIG. 4.

Ratio of Ly- γ to Ly- α for collision velocities between 300 km/s and 2500 km/s. Current data represented by open circles with 2σ error bars. Theoretical values used by D. Koutroumpa (2007) in her solar wind models are also shown, along with AOCC predictions [10]. MOCC calculations predict no significant Ly- γ [11].

TABLE I.

Energies and rates for electron transitions for C VI. Data statistically averaged over all j-states is obtained from <http://open.adas.ac.uk>.

Transition	$4f \rightarrow 3d$	$4p \rightarrow 3d$	$4d \rightarrow 3p$	$4s \rightarrow 3p$
Energy (eV)	23.8	23.8	23.8	23.8
Rate(s^{-1})	1.79×10^{10}	4.51×10^8	9.12×10^9	2.38×10^9
Transition	$4p \rightarrow 3s$	$4d \rightarrow 2p$	$4s \rightarrow 2p$	$3d \rightarrow 2p$
Energy (eV)	23.8	91.9	91.9	68.1
Rate(s^{-1})	3.98×10^9	2.67×10^{10}	3.34×10^9	8.38×10^{10}
Transition	$3s \rightarrow 2p$	$4p \rightarrow 1s$	$3p \rightarrow 1s$	$2p \rightarrow 1s$
Energy (eV)	68.0	459.4	435.6	367.5
Rate(s^{-1})	8.18×10^9	8.84×10^{10}	2.17×10^{11}	8.13×10^{11}
Transition	$3p \rightarrow 2s$	$4p \rightarrow 2s$		
Energy (eV)	68.1	91.9		
Rate(s^{-1})	2.91×10^{10}	1.25×10^{10}		