EUROPEAN FUSION DEVELOPMENT AGREEMENT

EFDA–JET–PR(01)110

K-D Zastrow et al

Double Charge Exchange from Helium Neutral Beams in a Tokamak Plasma

Double Charge Exchange from Helium Neutral Beams in a Tokamak Plasma

K-Zastrow[1], M Brix[2], C Giroud[3], A G Meigs[1], M G O'Mullane[4],
M Proschek[5], H P Summers[4]

[1]*EURATOM/UKAEA Fusion Association, Culham Science Centre, Abingdon OX143EA, UK*
[2]*Forschungszentrum Jülich GmbH, Institut für Plasmaphysik, EURATOM Association, D-52425 Jülich, Germany*
[3]*Association EURATOM-CEA, CEA Cadarache, F-13108 St Paul lez Durance, France*
[4]*Dept. of Physics and Applied Physics, University of Strathclyde, Glasgow, G4 0NG, UK*
[5]*Institut für Allgemeine Physik, TU Wien, Association EURATOM-ÖAW, A-1040 Wien, Austria*

Paper to be submitted for publication in Phys. Rev Letters

ABSTRACT
He neutral beams of 29.5 keV/amu have been injected into He plasmas on the JET tokamak. Thermal neutral He in its ground state forms along the beam trajectory due to resonant double charge exchange. This is the first observation of He-He double charge exchange in a laboratory plasma. The cross section is measured as $(2.05\pm0.49)\times10^{-16}cm^2$, about twice the value predicted by theoretical models and measured in ion beam into gas experiments. The signal from the halo is used to measure the plasma ion temperature and the frequency of toroidal rotation and can be used to infer the He ion density.

Charge exchange (CX) reactions between neutrals and impurity ions are responsible for strong spectral emission from plasmas at low impurity density. The reaction proceeds through capture into high *n* ion levels, followed by radiative cascades. This process is exploited for localized measurements of ion temperature, collective velocities and impurity densities using D beams [1,2,3,4,5]. With He beams, single CX rates to high *n* ion states are lower. There is however a different process, namely the double CX of neutrals with fully stripped impurity or helium ions to form He-like ions or neutral He. The inverse of this reaction, neutralization of He by collision of He ions with He-like impurities (C and metals), has been invoked in modeling to explain emission of fast neutral He from fusion plasmas [6]. There is however no direct evidence for this inverse process and the double CX from He beams to plasma ions has not previously been observed in a laboratory plasma.

A series of ^{4}He discharges was performed on JET (Joint European Torus) [7], with beam injection of ^{4}He at 118 keV (29.5 keV/amu). The plasma was swept radially, with simultaneous movement of magnetic axis and plasma boundary while keeping other plasma quantities (volume, current, magnetic field) constant, avoiding wall interaction at the extremes of the motion, see Fig.†1. This technique enhances the spatial resolution of edge and core diagnostics. Radial emission profiles of different He spectral lines were observed on successive identical discharges. To distinguish beam driven and passive emission, the beams were modulated in synchrony with the read-out of the spectroscopic signals. The beam emission, distinguished due to its Doppler shift, and emission in the wings of the un-shifted spectral lines with Gaussian line shape appear when the He beam is applied, see Fig. 2. The central part of the spectral line, due to cold neutral He at the plasma edge, and the part of the wings that correspond to the instrumental line shape, only respond weakly to the application of the beams. It is likely that this response is due to neutrals formed in the plasma by interaction with the beam which escape from the plasma and then give rise to enhanced edge recycling flux. The Doppler width and shift of the hot component can be used to derive a temperature T_{He} and a frequency of toroidal rotation ω_{He}, see Fig. 3. T_{He} is close to the local electron temperature as measured by LIDAR, and we find ω_{He}(rad/sec)$\approx10\times T_{He}$(eV). This behavior is expected for the ions in this kind of JET discharge and indicates that the emission is due to plasma ions neutralized by the beams, and that it is localized at the intersection of the He beams and the line-of-sight.

The intensity ratio for two different spectral lines of thermal He ($\lambda = 501.5$nm and $\lambda = 667.8$nm, both Singlet n=3 to n=2 transitions) is shown in the top part of Fig. 4, measured in two separate identical discharges. The ratio is in agreement with the ratio of the collisional radiative rate coefficients $X_{501.5} / X_{667.8}$. A hot component for spectral lines from n=4 has not been observed. We also measured the beam emission for two triplet n=3 to n=2 transitions, namely $\lambda = 706.5$nm and $\lambda = 587.6$nm. We cannot detect emission from a thermal population at $\lambda = 706.5$nm. For $\lambda = 587.6$nm a signal is discernible only for $\sqrt{\psi} > 0.8$, where ψ is the normalised flux surface coordinate. Such a low level of emission from triplet states is expected for electron impact dominated level populations at these electron temperatures. However at this wavelength the emission from the scrape-off layer, which is not completely subtracted by the beam modulation technique, dominates the spectrum due to the very low electron temperature, and an accurate measurement of the intensity of the hot component is not possible. All observations on line intensity ratios together suggest that there is no significant cascade following the formation of neutral He, and that the emission is dominated by excitation of He from its ground state.

If the density of neutral He, n_{He^0}, is established as equilibrium between double CX of plasma ions with beam neutrals and ionization we have

$$n_{He^2} \times n_{Beam} \times \sigma_{2CX} \times v_{Beam} = n_{He^0} \times n_e \times S \tag{1}$$

Here n_{He^2} and n_e are the density of He ions and electrons, respectively, and S is the collisional dielectronic ionization rate coefficient. The double CX reaction rate is given by its cross section σ_{2CX} (to be determined) and the beam velocity, provided $v_{Beam} >> v_{th}$. The intensity of the beam emission is a sum over the contribution from all metastable beam species, *m*, as $I_{Beam} = \sum_m n_{Beam,m} \times n_e \times \langle\sigma v\rangle_{\lambda,m}$ and emission from thermal He is given by $I_{thermal} = n_{He^0} \times n_e \times X_\lambda$, where $\langle\sigma v\rangle_{\lambda,m}$ and X_λ are collisional radiative rate-coefficients for the spectral line with wavelength λ. Beam emission lines are emitted from excited states with short lifetimes, typically a few 10^{-9} s, during which time neutrals move less than 10^{-2} m. Double CX, on the other hand, results in neutral He in the ground state as we have shown. Emission of spectral lines from these neutrals occurs after a subsequent collision with plasma electrons. The neutrals have time to move away from the point of birt, out of the line-of-sight of the spectrometer, with a mean free-path given by velocity and ionization rate. Since the resulting He distribution is cylindrically symmetric this is referred to as formation of a halo. In these experiments, 2keV neutrals have a mean free path of 0.25 m, compared to a typical beam diameter (FWHM) of 0.20 m due to beam divergence. In addition, a second beam is applied, which is not observed directly. The neutrals created by that beam can travel into the line-of-sight of the spectrometer. Our model for the intensity ratio therefore includes a correction factor α to account for this, thus

$$\frac{I_{thermal}}{I_{beam}} = \alpha \frac{n_{He^{2+}}}{n_e} \frac{X_\lambda}{S} \frac{\sigma_{2CX} v_{Beam}}{f_{m1}\langle\sigma v\rangle_{\lambda,m1} + f_{m2}\langle\sigma v\rangle_{\lambda,m2}} \tag{2}$$

Here, f_{m1} and f_{m2} are the fraction of beam atoms in the ground state (*m1*) $1s^{2}\,^{1}S$ and metastable state (*m2*) 1s2s ^{3}S, respectively. The atomic data for T_e=2 keV, $n_e=4\times10^{19}$ m^{-3} and $n_{He^{2+}} = n_e/2$, are taken from ADAS [8] as $S/X_{6678} = 223$ and $\langle\sigma v\rangle_{6678,m1}$ = 6.66×10^{-11} cm^3/s. Also we note that $\langle\sigma v\rangle_{6678,m2}$ = 1.55×10^{-8} cm^3/s so that a few percent population of *m2* can be important. We neglect $2s^{2}\,^{1}S$ as a metastable level (*m3*) since the rate coefficients for excitation of singlet lines from *m3* are only a factor 3 lower than those from *m1*, so that a very large level population would be necessary to play a significant role.

The measurement of the ratio of hot, thermal emission to beam emission for HeI 667.8 nm is shown in the central pane of Fig. 4 together with our model using $n_{He^{2+}} = 0.48 \times n_e$. The absolute value of the model has been fitted for $\sqrt{\psi} < 0.55$ with σ_{2CX} = (2.05±0.13) × 10^{-16}cm^2. which accounts for the presence of residual D as measured at the plasma edge. The error is due to the statistical error of the intensity measurements. The systematical error of αdue to a ±5 cm uncertaintiy of the alignment of the line-of-sight with respect to the beams in the vertical direction results in an additional $\Delta_{align}\sigma_{2CX}$ = ±0.13 × 10^{-16}cm^2.

The good agreement of the predicted radial profile shape in Fig. 4 is evidence that our observations are explained by double CX. The deviation for $\sqrt{\psi} > 0.8$ is probably due to enhanced beam emission driven by the fraction of the beam in metastable *m2*. The fraction required to explain the measurements is evaluated in the bottom pane of Fig. 4. The fall-off from the initial level of about 1% occurs over a few 10 cm since the cross-section for ionization for metastable He is much larger than that for ionization from the ground state, while collisional excitation from the ground state to the metastable level is slower than the ionization from the ground state. The initial level and decay length are quantitatively consistent with beam modeling [9].

For completeness we briefly describe the alternative model that spectral lines are emitted by neutral He as a result of two subsequent single CX events. Singly ionized He at several keV will escape from the active beam volume, where it was created, much faster than it is ionized by collisions. Since the escaping ions follow the magnetic field lines, this process is referred to as the formation of a plume. The equilibrium is given by

$$n_{He2} = n_{Beam} \times \sigma_{1CX} \times v_{beam} = n_{He+} \frac{v_{th}}{d_{Beam}} \tag{3}$$

The intensity of the spectral line emitted by thermal He in this model is given by $I_{thermal} = n_{He^+} \times n_{Beam} \times \sigma_{\lambda CX} \times v_{beam}$. Instead of its ratio to that of the beam emission, it is more convenient to derive

$$\frac{I_{thermal}}{I_{Beam}^2} \sim \frac{n_{He^{2+}}}{n_e^2} \frac{v_{Beam}^2}{v_{th}} \frac{\sigma_{1CX}\sigma_{\lambda,CX}}{(f_{m1}\langle\sigma v\rangle_{\lambda,m1} + f_{m2}\langle\sigma v\rangle_{\lambda,m2})^2} \tag{4}$$

Most of the terms on the right hand side of Eq.4 are constant in radius, and the radial dependence is of the form $1/n_e v_{th}$ which has its minimum on axis. The term on the left hand side of Eq. 4 on the other hand increases from the plasma edge towards the plasma centre by about a factor four in the experiment. This model can therefore be excluded.

Fig. 5 compares our result for σ_{2CX} to data from the ORNL collection [10] which agrees well with ADAS, to data from theoretical predictions [11,12,13,14] and to ion beam into gas measurements [15,16]. For comparison, the total beam stopping coefficient from ADAS at this beam energy, including electron and ion impact ionization as well as single and double CX, is $\sigma_{tot} \approx 5\times10^{-16}$ cm^2. Our result is about two to three times larger than most theories and data collections, and that obtained in ion beam into gas measurements. The apparent agreement of our measurements with the results by Belkic [12] is probably a coincidence, since our collision energy is at the lower limits of the range of that theory.

Our result for σ_{2CX} would increase if less He was present than we have assumed, thus increasing the discrepancy between our results and those obtained by others. The lower limit is $n_{He^{2+}} = 0.46 \times n_e$, due to C and metals, the upper limit is $n_{He^{2+}} = 0.5 \times n_e$. This results in a systematic error for the cross section of $\Delta_{fHe}\, \sigma_{2CX} = \pm0.20\times10^{-16}$ cm^2. Although this estimate may appear optimistic, it is in fact very conservative, because in contrast to the behavior in D plasmas, medium and high Z impurities are actually not detectable at low heating power in He plasmas. This is consistent with very low impurity production even in high power JET He plasmas [17]. For example CX spectroscopy of C with D beams in He plasma should detect fractions larger than 0.1%, whereas no signal is observed. Another indication that He is virtually undiluted is that the observed intensity ratio does not increase with time, whereas the plasma density increases by about 20% due to the addition of He by the beams.

The atomic data $\langle\sigma v\rangle_\lambda$,$X_\lambda$ and S in Eq. 2 also contribute a systematic error. Since all three quantities are derived from the same fundamental cross-section data, there is some cancellation of systematic errors. The overall uncertainty of the derived ratio is estimated to be 15%, which results in a systematic error $\Delta_{th}\, \sigma_{2CX} = \pm0.32\times10^{-16}$ cm^2.

With the cross-section for resonant double CX established, the signal from the halo can be used for He ion density measurements in discharges with $n_{He^{2+}}<n_e/2$. The main advantage is the self-calibration of the derived He ion density, when Eq. 2 is used. Errors in instrumental parameters, absolute calibration and to some extent alignment, do not propagate to the derived He density. The alignment error would cancel exactly if the system was built to encompass all of the beam and the halo. Also, there is no need to model the beam density, provided the initial metastable beam population has been fully ionized.

In summary, a halo of neutral He has been observed along the trajectory of the He beams in the JET tokamak. It has been shown that its formation is due to resonant double CX between the beams and plasma ions, leading directly to formation of neutral He in its ground state. This is the first experimental observation of He-He double CX between a neutral beam and plasma ions. The cross section at the beam energy of 118 keV (29.5 keV/amu) is measured as $(2.05\pm0.13\pm0.24\pm0.32)\times10^{-16}$ cm^2, where the first error is the statistical error, the second is the systematic error contributed by the experiment (alignment and fraction of He) and the third is the systematic error contributed by the atomic data for ionization and excitation. The value is about twice that predicted by most theoretical calculations, and previous ion beam into gas experiments. The signal from the halo is used to infer the plasma ion temperature, the frequency of toroidal rotation and can be used to measure the He ion density.

This work was performed under the European Fusion Development Agreement, and funded in part by EURATOM and the UK Department of Trade and Industry. M Proschek was supported by the Friedrich Schiedel Stiftung für Energieforschung.

REFERENCES

[1] R C Isler, Phys. Rev. Lett. **38**, 1359 (1977)
[2] R J Fonck *et al*, Appl. Phys. Lett. **42,** 239 (1983)
[3] R J Groebner *et al*, Appl. Phys. Lett. **43**, 920 (1983)
[4] P G Carolan *et al*, Phys. Rev. **A35**, 3454 (1987)
[5] A Boileau *et al*, Plasma Phys. Contr. Fusion **31**, 779 (1989)
[6] A A Korotkov *et al,* Phys. Plasmas **7**, 957 (2000)
[7] The JET Team, Fusion Technology **11**, 1-282 (1987)
[8] H P Summers, The ADAS User Manual – version 2.2 (2000), http://adas.phys.strath.ac.uk
[9] M Proschek, PhD Thesis, TU Wien 2001
[10] C F Barnett *et al*, Atomic Data for Fusion, Vol 1, ORNL-6086 (1990)
[11] K Kimura, J. Phys. **B21**, L19 (1988)
[12] D Belkic, Phys. Rev. **A47**, 189 (1993)
[13] W Fritsch, J. Phys. **B27**, 3461 (1994)
[14] K Tokesi and G Hock, J. Phys. **B29**, L119 (1996)
[15] R D DuBois, Phys. Rev. **A33**, 1595 (1986)
[16] R D DuBois, Phys. Rev. **A36**, 2585 (1987)
[17] V Phillips *et al*, Proceedings 23rd European Physical Society Conference on Plasma Physics and Controlled Nuclear Fusion, Madeira, Portugal, 18-22 June 2001

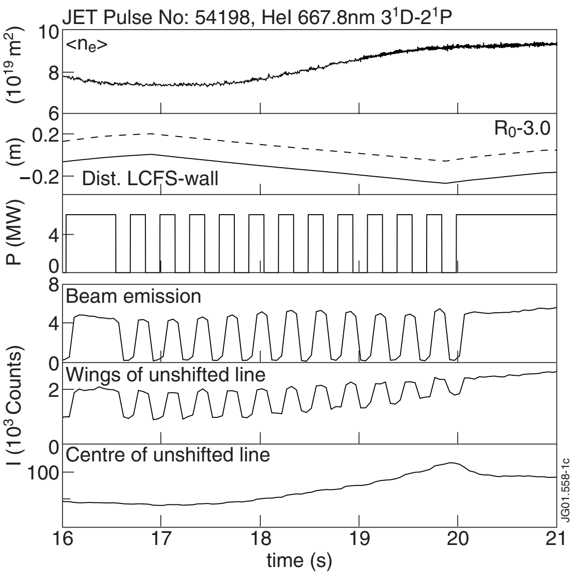

Fig. 1: Top half: Discharge parameters for swept plasma experiments with modulated beams: Line density responding to beam injection; magnetic axis position (R_0-3.0m) and outboard distance from last closed flux surface (LCFS) to the wall showing the slow sweep; modulated beam power. Bottom half: Intensity of HeI 667.8 nm in various sections of the spectrum in Counts/sec. When the He beam is applied, the beam emission and a large fraction of the wings of the un-shifted emission appear in the spectrum. The intensity of the centre of the unshifted line increases with density, and shows a weak increase with He beam power.

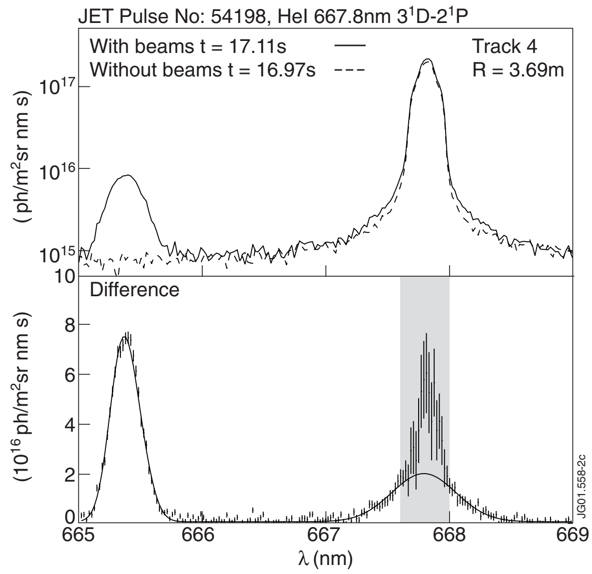

Fig. 2: Top: Spectrum of HeI 667.8 nm with and without He beams on a logarithmic scale. The beam emission is Doppler shifted to a lower wavelength. Bottom: Difference spectrum with statistical error bars. A hot component is apparent at the un-shifted position. The subtraction of the edge component is incomplete. To take this into account ±10 pixels (shaded area) around the position of 667.8 are excluded in the analysis of the difference spectrum and only the hot component is fitted.

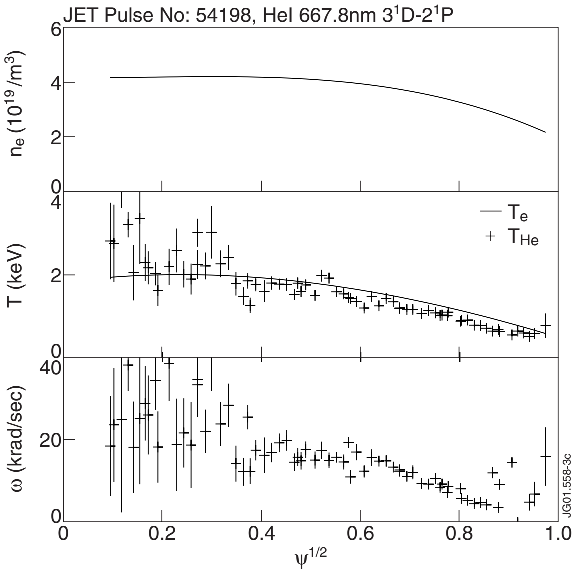

Fig. 3: Composite radial profiles for the discharge shown in Fig. 1 vs normalised flux coordinate, $\sqrt{\psi}$. The plasma is swept across the line-of-sight of the diagnostics, resulting in enhanced radial resolution. Top: Time averaged electron density profile from LIDAR, Middle: Time averaged electron temperature (solid line) from LIDAR and temperature derived from the hot component of HeI 667.8 nm. Bottom: Derived frequency of toroidal rotation.

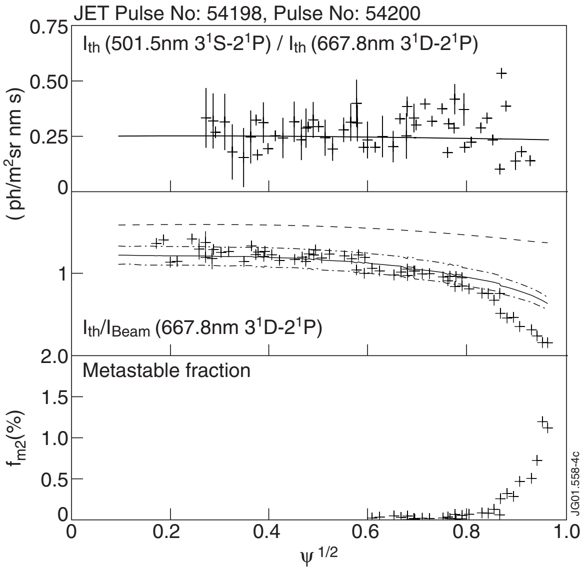

Fig. 4: Top: Ratio of two singlet lines from the hot component. HeI 501.5 nm has been measured in discharge #54200 and HeI 667.8 nm has been measured in discharge #54198. The error bars represent the statistical error. The solid line is the ratio of the rate coefficients. Middle: Ratio of hot component to beam emission for HeI 667.8 nm, both from #54198. The solid line is derived from Eq. 2. The confidence interval (dash-dotted line) includes statistical errors and the systematic error due to the uncertainty in the alignment. The dashed line excludes the probability for neutral He to escape from the line-of-sight. Bottom: Metastable fraction required to explain the deviation of the data from the model.

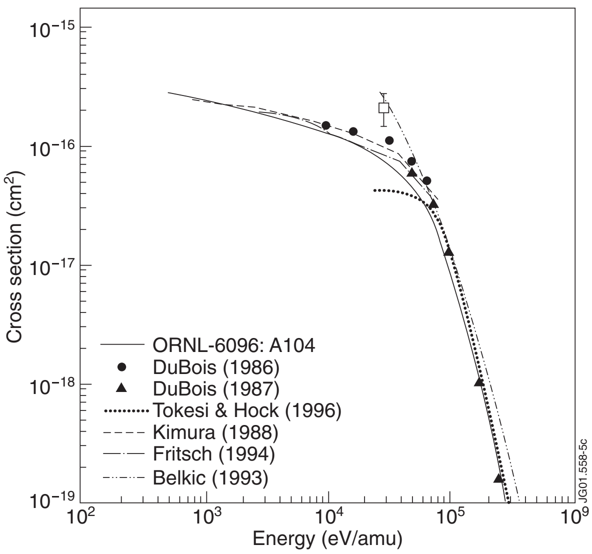

Fig. 5: Comparison of the cross-section for double CX for neutral beams and plasma ions, derived in this paper, (open square) with previous data from ion beam into gas experiments (symbols) and theoretical models and data collections, respectively (lines).