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論文内容の要旨

The charge transfer process is one of the dominant processes in plasmas with high neutral abundance, e.g., the edge region or divertor of tokamak plasmas. Recently, double charge transfer processes of multiply charged ions with molecules are of great interest, because it was reported that a certain process ($He^{2+}+H_2$ -> $He^*+H^++H^+$) has a large cross section. In this case, the cross section is larger than single one in low energy collisions (E<1000eV) and observed to be the Langevin type; the cross section is proportional to $E^{-0.5}$ and kept large even under low temperature conditions.

We have then considered possibilities of large cross sections for double charge transfer processes of carbon ions (dominant impurities in present fusion oriented plasmas) in collision with H_2. According to Over-the-Barrier Model, double charge transfer of C^{3+} ($C^{3+}+H_2$ ->$C^{+*}+H^++H^+$) is expected to be similar to He^{2+}-H_2 process on the analogy of recombination energies of He^{2+}-> He[1s3l] (55.9eV) and C^{3+}->C^{+*}(50～60eV), which can be regarded as energetically resonant. However, the cross section for this process has not been measured, though that for single charge transfer was already reported.

In this study, we have tried to find that the double charge transfer process in C^{3+}-H_2 collision has a large cross section in low energy collisions and plays an important role in the edge region of tokamak plasma with spectroscopic method.

First, pulsed H_2 gas injection experiment was carried out in TPD-II steady-state plasma apparatus (T_e～5eV, n_e～$10^{14}cm^{-3}$), which produces a carbon doped helium plasma, to investigate charge transfer processes of carbon ions with neutrals. Immediately after the start of H_2 gas injection, emissions of hydrogen lines and molecular bands begin to be enhanced obviously. The inelastic collisions of electrons with H and H_2 cause a rapid fall of electron temperature in the target plasma. Since this fall of electron temperature decreases electron impact excitation rates, most of the line emission intensities of helium, carbon, and their ions in the target plasma decrease rapidly in a few milliseconds. However, CII line emissions in doublet states show anomalous enhancements and were investigated in detail under two operating modes: a mode with a high abundance of C^{3+} in the plasma (C^+: C^{2+}: C^{3+} =10: 8: 4) and a mode with a low abundance of C^{3+} (10: 7: 1). These two modes are defined by controlling a flow of CO gas introduced into the plasma. The observed intensities of CII doublet lines, e.g., 54.3nm ($2p^2P$-$6d^2D$) and 657.8nm ($3s^2S$-$3p^2P$), increase rapidly with significant dependence on the abundance of C^{3+}. These increases appear so fast (in a few milliseconds) that the three-body and radiative recombination processes of C^{2+} may not take place. Furthermore, dependence on the abundance of C^{3+} also suggests that the enhancement of CII doublet lines are not due to recombination processes of C^{2+}, but of C^{3+}. While in quartet transitions of C II, line intensities decrease after the gas injection similarly with other HeI, HeII, CIII, and CIV lines and are almost independent of the C^{3+} abundance. These results, which show the significant influence of the C^{3+} concentration on the CII line intensities, are the evidence that a charge transfer of C^{3+} causes the enhancement of CII doublet line emission.

Then, spatial distributions of line emissions were measured to identify whether a charge transfer process takes place with H or H_2. Enhanced CII line emissions are distributed in a hollow shape, though all of the carbon line emissions have a Gaussian like distribution in the steady-state. However, H_α emission has a Gaussian-like distribution which is obviously narrower than that of the enhanced CII lines. The CII hollow distribution thus implies that the increased CII line emissions are not attributed to a charge transfer with H. On the other hand, H_2 is distributed in a hollow shape because the H_α emission indicates decay of H_2 by the target plasma. The double charge transfer of C^{3+} with H_2 is therefore thought to cause enhancement of CII doublet lines after the H_2 gas injection.

The total rate coefficient which causes the enhancement in CII line emissions was estimated to be $3\pm2\times10^{-8}cm^3s^{-1}$. This rate is in relatively well agreement with the value ($2\times10^{-8}cm^3s^{-1}$) predicted with the Langevin cross section, and equivalent to the cross section of $\sim10^{-14}cm^2$ in several eV.

In addition, one important characteristic of charge transfer process is a selectivity of capturing electronic state. As contrast with the clear state-selective capture in He^{2+}-H_2 collision, the product-states in doublet configuration show a gradual dependence on the excitation energy. However , there is an large difference between the doublet and quartet states. An electron seems to be mainly captured to a doublet state.

Based on the above observations, we have investigated the contribution of this double charge transfer process in the edge plasma of JIPP T-IIU tokamak.

UV-Visible spectroscopic system was used to observe line emissions from the edge plasma of the JIPP T-IIU. One difficulty is in the measurement of concentration of H_2 at the edge region because of its weak band emissions. In this experiment, concentration of H_2 ($\sim10^9cm^{-3}$) was estimated from observation of HeI lines in H_2/He discharge with the well established double charge transfer cross section in He^{2+}-H_2 collision. CII line emissions are measured from 0msec to 20msec after the breakdown of the discharge. As impurities are successively ionized with increasing of T_e and n_e, population densities of an ion are governed dominantly by electron impact excitation processes (ionizing phase). CII spectral distribution in the ionizing phase is therefore regarded as a reference distribution which is not affected by recombination processes, particularly by charge transfers with H and H_2.

From 60msec after the breakdown of the discharge, the plasma current is kept constant (current plateau phase) with the plasma parameters of T_e=1.5keV and $n_e=1.5\times10^{13}cm^{-3}$ at the plasma center. In this phase, recombination processes are expected to have large effects on the ionization balance and spectral distributions. The difference between the CII spectral distributions in the ionizing and the current plateau phase thus corresponds to the influence of charge transfer processes. Of course, each absolute line intensity of CII changes significantly from the ionizing phase to the current plateau phase as plasma parameters change. However, variation of each absolute line intensity is not important to find out the contribution of recombination processes for our spectroscopic observation. The variation of CII spectral distribution shows two obvious characteristics: first, it is significant that the ratios of doublet lines are largely different from those of quartet lines, secondly the ratios of doublet lines show a gradual dependence on excitation energies. The CII spectral distribution at the edge plasma of JIPP T-IIU tokamak was compared with the result of H_2 gas injection experiment in TPD-II apparatus. Fairly good agreement between the two observations shows that the change in CII spectral distribution is mainly caused by the double charge transfer of C^{3+} with H_2.

It is concluded that the Langevin-type double charge transfer processes (C^{3+} -H_2 and He^{2+} -H_2) are thought to be dominant recombination processes in the edge region of high temperature plasma and divertor plasmas.

論文の審査結果の要旨

本研究論文は定常プラズマ及びトカマク装置の周辺部に於ける不純物イオンと水素分子との２電子移行過程についての実験的研究をまとめたものである。

既に知られていたヘリウム２価イオンと水素分子との２電子移行反応が大きな断面積を持つことに着目し、炭素３価イオンと水素分子との２電子移行反応$C^{3+} + H_2 \rightarrow C^{+*} + H^{+} + H^{+}$も同様な共鳴効果によって大きな断面積を持つと推測した。これを調べるため、直線定常プラズマ装置であるＴＰＤ－Ⅱ装置で実験を行った。炭素イオンを混入させたヘリウムプラズマに水素ガスを噴射すると、各原子、イオンからの発光は電子温度の減少とともに急激に減衰する。しかし、炭素３価イオンを多く含む放電モードにおいて幾つかのＣⅡ線は逆に強度が増大することが観測された。一方、炭素３価イオンが少ない放電モードに於ては先の増光現象は殆ど観測されず、増光現象が電荷移行反応に起因すると考えられる。さらにＣⅡ線とH_{α}の動径方向の空間分布が異なることから、この増光現象において水素分子が直接関連していると考えられる。それらを総合すると、ＣⅡの増光現象は２電子移行過程$C^{3+} + H_2 \rightarrow C^{+*} + H^{+} + H^{+}$に依るものであると結論される。観測された各ＣⅡ線の増光度は各準位への相対的な２電子移行反応速度と見なすことができ、全体の２電子移行反応速度はおよそ10^{-8} cm^3/sと非常に大きな値となり、予測されたように共鳴効果によるものと考えることができる。

次に、このような２電子移行過程をJIPP T－IIUトカマク装置の周辺プラズマにおいて調べた。不純物イオンの存在量は比較的良く調べられている反面、水素分子の存在量に関しては余り調べられていない。そこで、既に反応断面積が測定されている２電子移行反応$He^{2+} + H_2 \rightarrow He^{*} + H^{+} + H^{+}$を観測し、周辺プラズマに於て２電子移行がどの程度起きているか、またどの程度水素分子が存在するかを評価した。ヘリウムの２電子移行過程に伴う選択的電子捕獲特性によるHeI線分布の観測により、周辺部に於てこの過程が電子励起と同程度の寄与を持つことが判った。また、水素分子がほぼ電子密度の数パーセント程度存在していると見積もられた。

更に、JIPP T－IIUトカマクに於てＣⅡ線を観測し、炭素３価イオンの２電子移行反応を調べた。ＣⅡ線は放電の立ち上がり時に於ては、ほぼ完全な電離進行状態のプラズマと見なすことができる。一方、定常状態では高電離イオンの再結合の寄与が大きくなるので、両状態での各線スペクトルの相対強度の変化は再結合の寄与を表わすと考えられる。各ＣⅡ線は立ち上がり時に較べて定常状態では温度、密度が増加するため絶対強度は増すが、それらの相対的な強度変化の度合は、ＴＰＤ－Ⅱ装置で観測された相対的な２電子移行反応速度と良く一致していることが判った。よって、各ＣⅡ線の相対強度の変化は炭素３価イオンの２電子移行反応によるものであると考えられる。

従って、不純物イオン（炭素、ヘリウム）と水素分子の２電子移行過程が周辺プラズマにおいてリサイクリング等の物理過程に大きな寄与を持ち得ることが初めて見い出され、核融合装置でのダイバータプラズマ等を理解する上で、水素分子と不純物イオンとの２電子移行過程が重要な役割を果たし得ることを示唆する貴重な知見を得た。

よって、本審査委員会は、新しい知見を得た成果と当該分野への貢献の程度から判断して、本論文が博士学位論文として十分の資格があると認めた。

論文審査委員全員の前で岩崎君に対して口頭試問を実施し、論文内容に関する質疑及び関連する分光学やプラズマ物理などの基礎知識についての試験を行った。その結果、質疑への対応は的確であり、且つ、十分に研究内容を理解していることが示された。基本的事項及び関連している物理について十分に理解していると考えられる。また、本論文や投稿論文が英語で書かれていて、英語の学力についても十分であると認められた。

以上により、本試験は合格とした。