Charge changing processes of MeV ions penetrating through liquid spray: formation of negative ion and neutral atom beams

S. Ter-Avetisyan[1, 2], M. Borghesi[3], M. Schnürer[4], J. Bränzel[4], S. Jequier[5], and V. Tikhonchuk[5]

[1]*Center for Relativistic Laser Science, Institute for Basic Science (IBS), Gwangju, Korea*
[2]*Department of Physics and Photon Science, GIST, Gwangju, Korea*
[3]*School of Mathematics and Physics, The Queen's University of Belfast, BT7 1NN, UK.*
[4]*Max Born Institute for Nonlinear Optics and Short Pulse Spectroscopy, 12489 Berlin, Germany.*
[5]*Centre Lasers Intenses et Applications, University Bordeaux, CEA, CNRS, 33405 Talence, France.*

The scenario of "electron capture and loss" for the formation of negative ion and neutral atom beams with up to MeV kinetic energy has been validated and its generic nature is demonstrated by sending the fast positive ions accelerated from a laser plasma source through a cold spray. Formed neutral atoms or negative ions have nearly the same momentum as the original positive ion.
Experiments are realised for protons, carbon and oxygen ions and corresponding beams of negative ions and neutral atoms are obtained. The electron capture and loss phenomenon is confirmed to be the origin of negative ion and neutral atom beams. The equilibrium ratios of different charge components and cross sections have been measured. The method appears to be general and allows creation of various neutral atom and negative ion species together with the characteristics similar to the positive ion source.

1. Introduction

Negative ions play a major role in a number of areas of physics and chemistry, for high current tandem accelerators, for ion beam microscopy and lithography. They can be easily neutralised into neutral atom beam. Nowadays the neutral atoms are considered essential in the fusion experiments for additional heating of the plasma.

There is a strong fundamental interest in negative ions: here in screening of nucleus the inter–electronic interactions become relatively more important than the electron–nuclear interactions. The interplay of these attractive and repulsive interactions allows better understanding of atomic physics. Here electron correlations play an important role.

The way to generate powerful neutral atoms beams is to produce a positive and negative ions, to accelerate them and then to neutralise the beam. However, the efficiency is very low.

After reviewing the relevant theoretical and experimental background on negative ion acceleration mechanisms this presentation will discuss the results of recent experiments where energetic (~MeV energies) negative ion and neutral atom beams have been generated at the passage of energetic positive ions through a liquid spray [1]. We are demonstrating the efficient production of neutral atom beams from MeV positive ions in the electron capture and loss processes, where the energy and momentum of the particle is preserved. Efficient generation of neutral hydrogen, carbon and oxygen atom beams have been demonstrated. The process is rather general and different neutral atom beams can be generated. In the present paper we will be demonstrating how the new achievements in positive ion source technology can be directly transferred to negative ion and neutral atom beams.

We will discuss the physical aspects of the phenomena and open problems. At the moment we do not have clear explanation, but it is suggestive that the processes are more complex than the considered single electron capture and loss, or the shell effects in the electronic structure of the projectile ion and/or target atoms may influence the probabilities.

Substantial work would be required for sophisticated model analyses in order to better understand the dynamics involved in the electron transfer processes.

2. Experimental set up

The experimental arrangement is presented in Fig. 1. The ion beam acceleration is realized from 5 µm polymer CHO or Ti foil targets by irradiating them with 40 fs, 1 J Ti:Sapphire laser pulses at an intensity of 5×10^{19} W/cm^2. A well characterised either water [2] or ethanol [3] spray positioned at the distance of 4 cm from the foil target allowed us to study the ion – spray interaction. The Thomson spectrometer enables absolute measurements of both positive and negative ions, in a single shot.

The interaction region of the spray has a thickness of up to 2 mm and consists of droplets with a diameter of 150 nm in the case of water (H_2O) or 180 nm in the case of ethanol (C_2H_5OH)

sprays. The average molecular densities are 2×10^{18} and ~10^{19} cm^{-3} for the water and ethanol, respectively. In the experiments the width of the spray and thus the propagation length of ions through the spray was controlled using a skimmer.

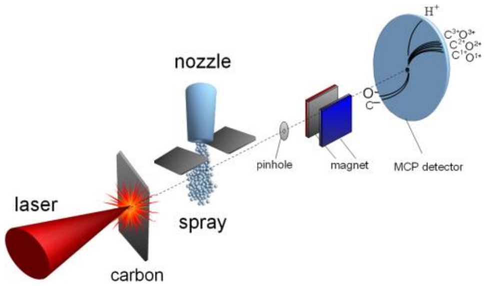

Fig. 1. Experimental setup for investigation of electron capture and loss processes at the passage of fast positive ions through a liquid spray target.

3. Result and discussion

In Fig. 2 Thomson-parabola traces of carbon ion and proton spectra a) accelerated from carbon foil target and b) accelerated from carbon foil target and propagating through the water spray are shown. From carbon foil target only positive carbon and oxygen ions with the charge states 1+ up to 4+ and H+ are visible. The bright circle in the upper right corner is formed by neutrals and energetic photons moving along the axis of the spectrometer. When the ion beam was propagating through the spray charge distribution is changed and C^- and O^- are appearing.

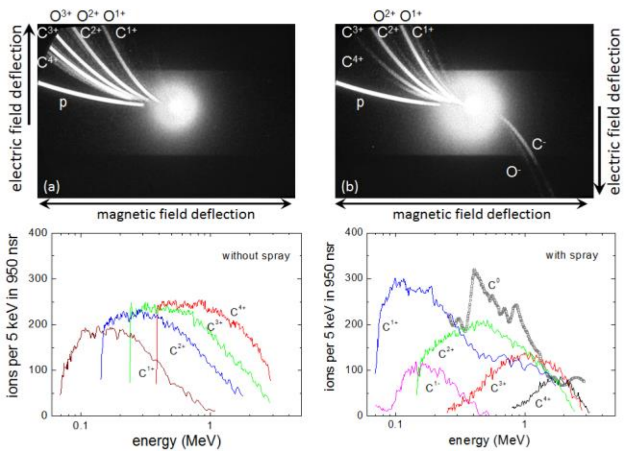

Fig.2. a) and b), Thomson-parabola traces of carbon ion and proton spectra from carbon foil target with and without spray. Below are the spectra deduced from images shown in a) and b).

Because the propagation of carbon and oxygen ions through a spray is highly collisional (free path length is <50 µm), the measured strong modification of ion spectra and appearance of C- and O- ions can be assigned to the electron capture and loss processes during ion propagation through the spray. If no interaction with the spray occurs (spray generator is off) the cut off energies of carbon ions are increasing with the ion charge state (Fig. 2). On the contrary, after an interaction with the spray C^{q+} ions have similar cut-off energies which show that the recombination from the q+1 to the q state occurs without losing energy. Moreover, the original feature of the ion spectrum exhibiting an increase of energy cutoff values with the charge state was lost. Ions recombine and their charge states have been redistributed according to the probabilities of electron capture and loss processes inside the spray. It results also in the appearance of ions with a lower charge state with higher energies (compare spectra in Fig.2.). In particular, the fastest C^+ and C^{2+} ions are, in fact, the ions with initially a higher charge that captured electrons while conserving their energy. Thus, the C^- ions are formed.

The electron capture and loss scenario of negative ions formation implies also the existence of fast neutral atom beams. Indeed, energetic beams of hydrogen (H^0) and oxygen (O^0) atoms have been also measured.

The quasi-classical analysis of the capture and loss of an electron in collisions of a fast ion with atoms in rest suggests that the maximum cross section corresponds to the projectile velocity comparable with the orbital electron velocities υ_0 ($\upsilon_0 = e^2/\hbar$ is the Bohr velocity) of an atom in rest. However the data for the cross sections of these processes reported in a literature are very limited or scattered, especially for the energies reported here (from 100 keV to a few MeV).

Subsequent investigations are required to further elucidate the negative ion formation scenario. It is clear that complex collision systems require a sophisticated model in order to better understand the dynamics involved in the electron transfer processes. Until such a model is available, the present experiments open a possibility for measuring the ratios of the cross sections of electron capture and loss to benchmark future theoretical models. They demonstrate a possibility of efficient neutralisation of carbon and oxygen ions with energies up to MeV.

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