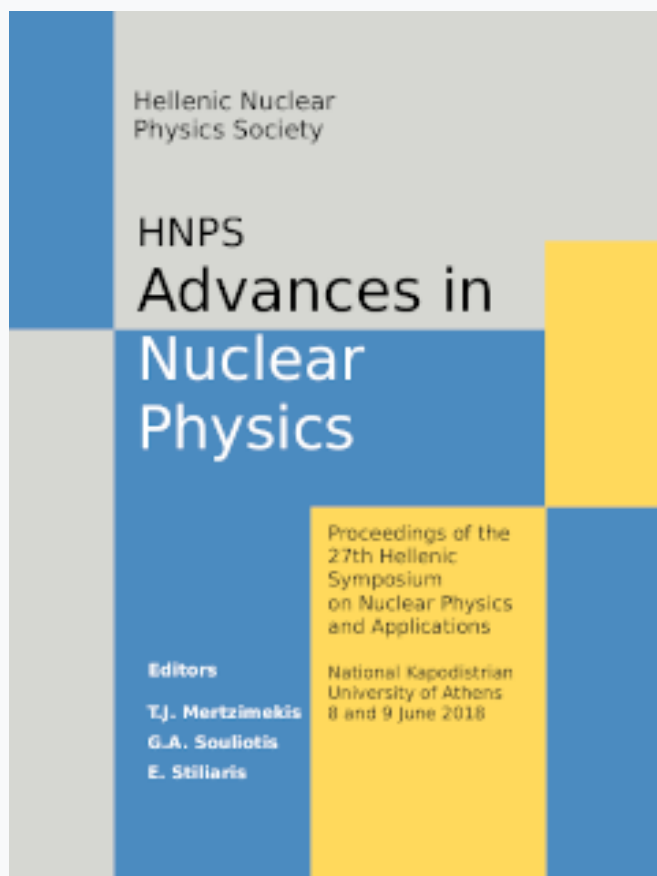


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# Production of $C^{4+}(2s2p\ ^3,^1P)$ hollow states in collisions of 6-18 MeV $C^{4+}(1s^2, 1s2s\ ^3S)$ mixed-state beams with gas targets

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**Abstract** Normalized electron yields of the formation of  $2s2p\ ^3,^1P$  states from the metastable states  $1s2s\ ^3,^1S$  and from the ground state  $1s^2\ ^1S$  were obtained in 6-18MeV  $C^{4+}$  collisions with  $H_2$ , He, Ne and Ar gas targets. The method of zero-degree Auger projectile spectroscopy was used to detect electrons emitted in the Auger decay  $C^{4+}(2s2p\ ^3,^1P) \rightarrow C^{5+}(1s) + e^-$  with high resolution. These states are of particular importance in the detailed study of fundamental excitation mechanisms, i.e. electron-nucleus excitation, electron-electron excitation and electron-electron excitation with spin exchange. Currently, the role of the above mechanisms in the production of the  $2s2p\ ^3,^1P$  states is investigated utilizing variable  $1s2s\ ^3S$  metastable fraction beams as a function of collision energy and target species. Our latest results are presented.

**Keywords** Auger electron spectroscopy, ion-atom collisions, electron-electron excitation, electron-nucleus excitation, zero-degree Auger projectile spectroscopy

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## INTRODUCTION

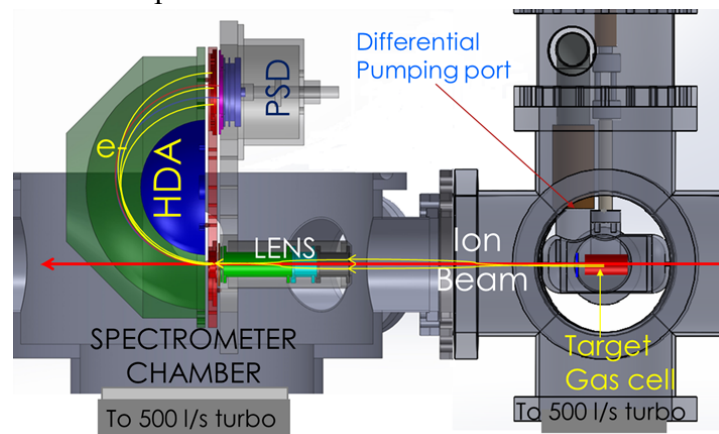
In ion-atom collisions basic processes, such as excitation and ionization, are attributed not only to the Coulomb interaction between the excited electron and the perturbing nucleus (e-n interaction), but also to the “spectator” electrons that can also participate in the collision either passively by screening the charge of the perturbing nucleus, or dynamically by interacting directly with the excited electron through an e-e interaction [1,2]. Both e-n and e-e interactions are usually present simultaneously making it difficult to experimentally separate one from the other [3]. Considerable effort in studying these mechanisms has been made in the past [3,4]. Recently, our interest has been focused on the strong production of the  $2s2p\ ^3P$  and  $^1P$  states in collisions of mixed-state He-like beams with gas targets. Here, we present new results on the production mechanisms of the doubly-excited  $2s2p\ ^3,^1P$  hollow states, obtained in collisions of 6-18 MeV  $C^{4+}(1s^2, 1s2s\ ^3S)$  mixed-state beams with  $H_2$ , He, Ne and Ar gas targets. Of particular importance is the fact that the amount of metastable fraction has been determined by a new in situ technique already presented [5].

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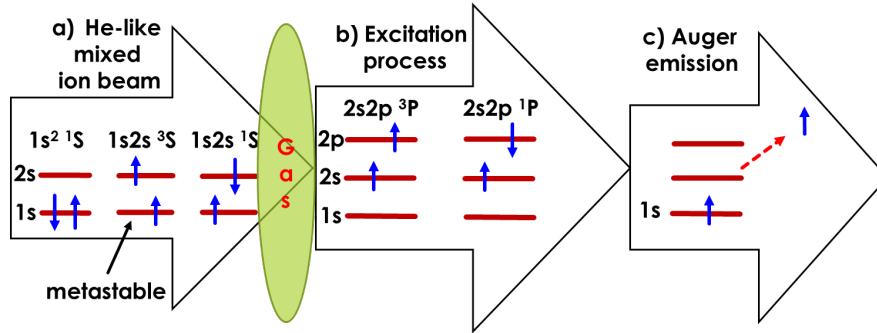
## EXPERIMENTAL SETUP

The electron excitation experiments were performed at the N.C.S.R “Demokritos” Institute of Nuclear and Particle Physics using the 5.5 MV tandem Van de Graaff accelerator.  $C^{4+}$  ions were accelerated to energies between 6 -18 MeV and collided with gas targets ( $H_2$ , He, Ne, Ar). The method of zero-degree Auger projectile spectroscopy (ZAPS) [6] was used, in which, the projectile emitted electrons are detected at zero degrees, along the beam direction (see Fig. 1). A hemispherical electrostatic analyzer (HDA) is placed in the path of the ion beam and used for energetically separating the emitted electrons. Our experimental apparatus includes also a doubly differentially pumped cylindrical cell hosting the gas target, an electrostatic lens at the entrance of the HDA used for focusing and preretarding the electrons prior to the entrance into the HDA, and a two-dimensional position sensitive detector (2-D PSD), where the electrons position (x,y) in the detection plane of the PSD is recorded.



**Fig. 1.** The experimental apparatus used for zero-degree Auger projectile spectroscopy. From right to left, the ion beam (red horizontal arrow) passing through the gas cell colliding with the target gas and traverses the lens and HDA. Electrons from the resulting projectile autoionizing states, emitted in the beam direction, enter the spectrograph to be energetically analyzed and recorded by the PSD.

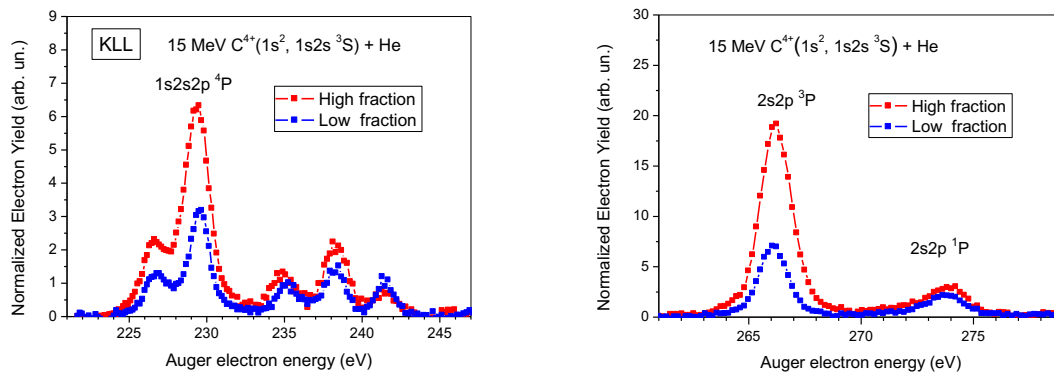
He-like ion beams are typically delivered in a mixed state by tandem accelerators, in which both the ground ( $1s^2$ ) and the long-lived (also termed *metastable*) excited states ( $1s2s\ ^3,^1S$ ) coexist. The percentage of each component in the mixture is determined from the way the ion beam is produced. In a tandem Van de Graaff accelerator the negatively charged incoming ion beam produced at a sputter ion source is stripped off some of its electrons by passing through a solid or a gaseous medium to become positively charged [7]. Typically, the higher the density of the stripping medium, the larger the metastable ( $1s2s\ ^3,^1S$ ) component in the beam [8]. As shown in Fig. 2 the positively charged mixed ion beam collides with a gas target of our preference forming the excited states  $2s2p\ ^3,^1P$ . Variable amounts of metastables can be produced, depending on the stripping medium and energy, providing an additional tool for the investigation of the formation mechanisms of the  $2s2p\ ^3,^1P$  states.



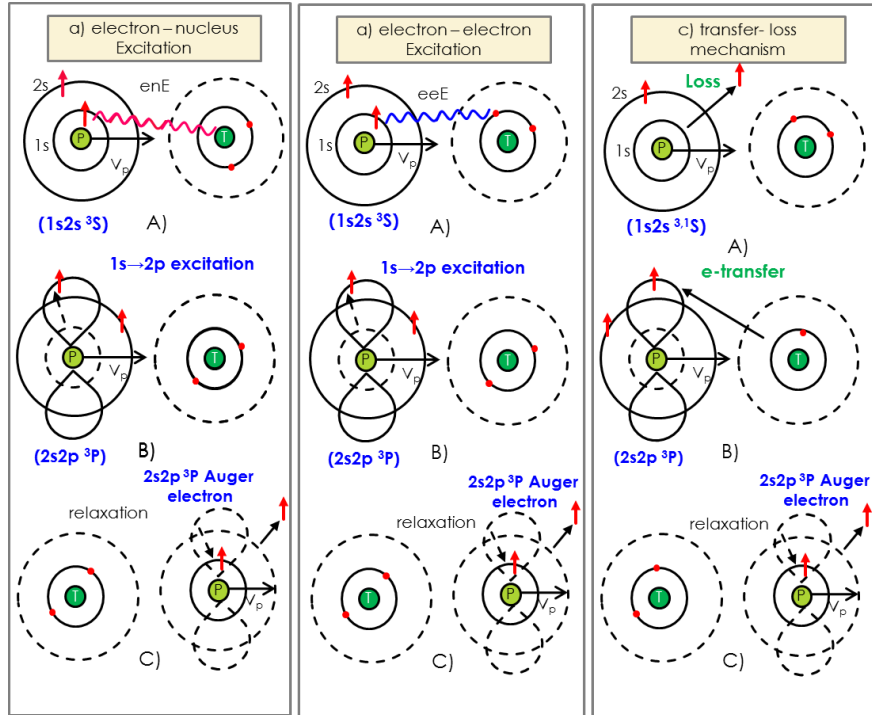
**Fig. 2.** a) The incident He-like beam comes in a mixture of three states, b) after the collision of the ion beam with the gas target, the projectile ion is excited to the  $2s2p\ ^3P$  states, c) subsequently, the excited ion relaxes by Auger decay.

## RESULTS AND DISCUSSION

In Fig. 3, we present zero-degree Auger electron KLL spectra obtained in collisions of a  $C^{4+}$  ion beam with a high  $1s2s\ ^3S$  fraction ( $\sim 14\%$ ), compared to similar spectra obtained with a lower  $1s2s\ ^3S$  fraction ( $\sim 6\%$ ). It is clearly seen, that some of the Auger lines suffer a drastic change in intensity, while others remain practically unaffected in the change from high to low metastable fraction. Thus, for some lines the contribution from the metastable state  $1s2s\ ^3S$  is much larger than others. According to our earlier studies [9,10], the  $1s2s2p\ ^4P$  state is produced by direct  $2p$  capture to the  $1s2s\ ^3S$  metastable component of the beam and its intensity is therefore proportional to this metastable fraction. Similarly, the  $2s2p\ ^3P$  line, seems to be strongly affected by the change in the  $1s2s\ ^3S$  metastable fraction, from which we conclude that the  $2s2p\ ^3P$  state must also be primarily produced from the  $1s2s\ ^3S$ . On the other hand, the  $2s2p\ ^1P$  line intensity is relatively unaffected by the change in metastable content and thus must be primarily produced from the much larger ground state  $1s^2\ ^1S$  fraction.



**Fig. 3.** Normalized zero-degree Auger electron KLL spectra produced in collisions of  $15\text{ MeV } C^{4+}$  ions with either a high  $1s2s\ ^3S$  metastable fraction (red line) or a lower fraction (blue line). The two spectra are different energy regions of the recorded KLL spectrum.

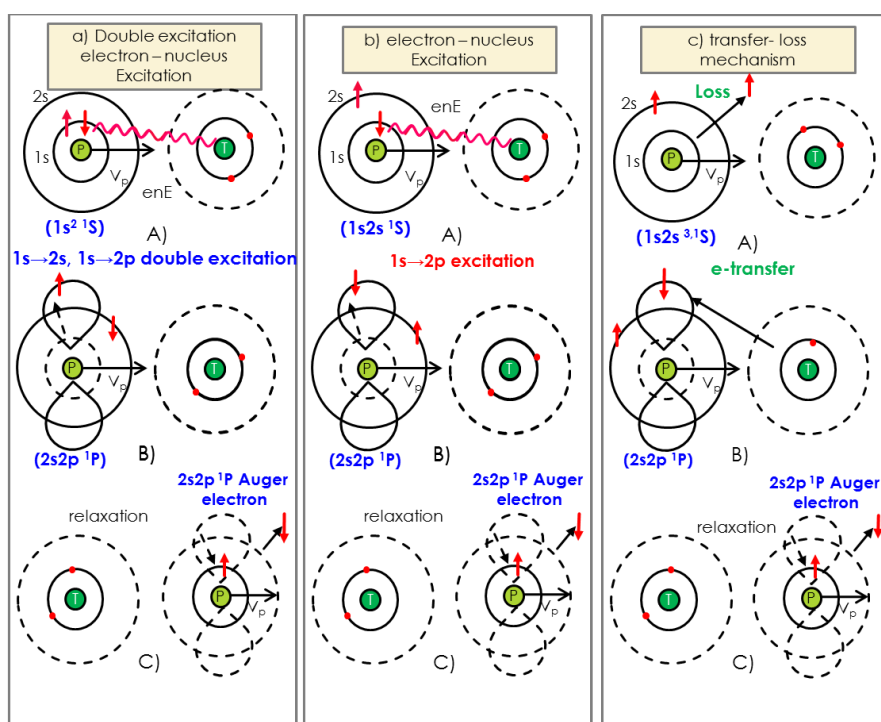


**Fig. 4.** Mechanisms leading to the production of the  $2s2p^3P$  state by single excitation of a core electron in the  $1s2s^3S$  initial state: a) Electron-nucleus excitation (enE) interaction, b) Electron-electron excitation (eeE) interaction, c) Transfer Loss (TL) mechanism. Note that for the TL mechanism the initial state of the ion beam can be either  $1s2s^3S$  or  $1S$ .

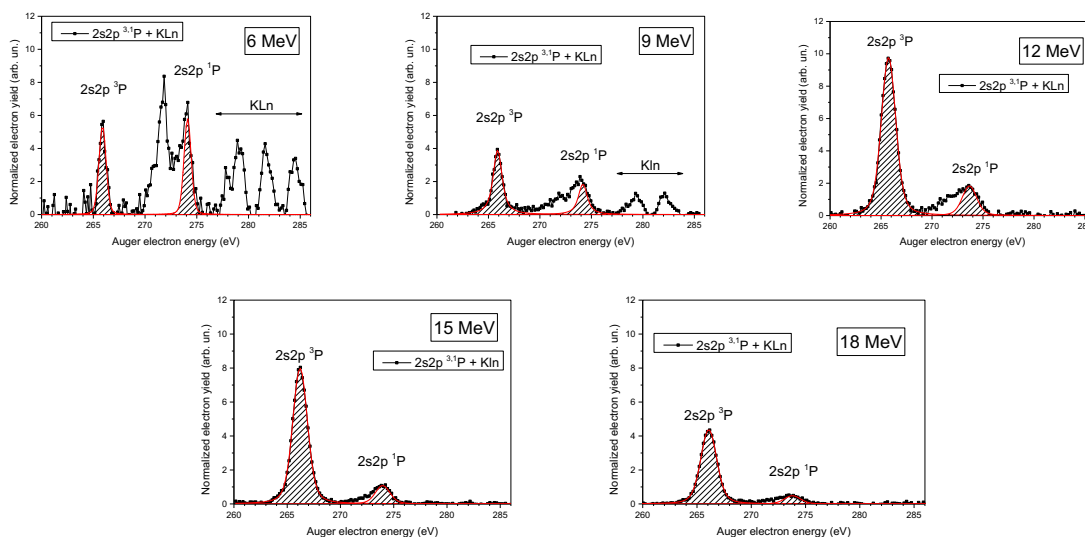
The potential formation mechanisms are shown in Fig. 4 and Fig. 5. For the  $2s2p^3P$  state we can safely assume that it can be primarily formed from  $1s2s^3S$  metastable state through  $1s \rightarrow 2p$  single excitation by either electron-nucleus (e-n) or electron-electron (e-e) interaction. Secondary processes involving the  $1s2s^3,1S$  metastable states, such as transfer-loss (TL), where the ionization of a projectile electron (loss) occurs simultaneously with the transfer of a target electron [4] are also possible, but with much lower probability. Contributions from the  $1s2s^1S$  state, even though its fraction is in general very small ( $< 5\%$ ) and does not seem to appreciably contribute to the doubly excited Li-like KLL states, its contribution to the  $2s2p^3,1P$  states needs further consideration. For example, the  $2s2p^1P$  state can be populated by direct  $1s \rightarrow 2p$  single excitation from the  $1s2s^1S$  state, by double excitation from the ground state  $1s^2^1S$ , by  $1s \rightarrow 2p$  single excitation with exchange from the  $1s2s^3S$  or by TL from either the  $1s2s^3S$  or  $1S$  states (see Fig. 5).

In Fig. 6 we present measurements of zero-degree Auger electron spectra obtained in collisions of 6-18  $C^{4+}$  with He targets. We can observe that the production yield of  $2s2p^3P$  increases with the energy reaching a maximum at around 12-15 MeV and then slightly decreases again, while for  $2s2p^1P$  the maximum occurs much earlier at 6 MeV from which the probability keeps dropping with increasing collision energy. Concerning the  $2s2p^3P$ , this behavior can be explained by the dependence of the cross section of the  $1s \rightarrow 2p$  excitation from the collision energy and the variation of the fraction of  $1s2s^3,1S$  of the ion beam which also

depends on the projectile's energy. For the  $2s2p\ ^1P$  state production a smoother behavior is observed, possibly indicating a strong dependence from the  $1s^2\ ^1S$  ground state.



**Fig. 5.** Same as in Fig. 4, but for the  $2s2p\ ^1P$  state: a) double enE from  $1s^2\ ^1S$  initial state, b) single enE from the  $1s2s\ ^1S$  initial state, c) TL mechanism from either  $1s2s\ ^3S$  or  $^1S$  initial state.



**Fig. 6.** Energy dependence of the  $2s2p\ ^{3,1}P$  normalized yields. As the collision energy increases, the  $2s2p\ ^3P$  yield increases reaching a maximum around 12-15 MeV and then decreases again, while the  $2s2p\ ^1P$  yield gradually decreases from a maximum around 6 MeV. KLn Auger lines indicated are mostly due to  $nl$  capture to the metastable component leading to higher-lying  $1s2s(^3S)nl\ ^2L$  states.

## CONCLUSIONS

In our experiments we used the naturally occurring mixed state ion beam of  $C^{4+}$  ( $1s^2, 1s2s^3, ^1S$ ) in collisions with various gas targets ( $H_2, He, Ne, Ar$ ) to investigate the production mechanisms of  $2s2s^3, ^1P$  doubly excited states. We have measured absolute electron yields of  $2s2p^3, ^1P$  for which we will soon present the production cross sections with comparisons to calculations using the 3e-AOCC method [11]. Using beams with different  $1s2s^3S$  fractions we have investigated the origin of each of the produced  $2s2p$  states. In the near future we plan to continue an isoelectronic study using different He-like ion beams (e.g.  $Li^+, B^{3+}, N^{5+}, O^{6+}$ , etc) and we will also present a theory that will be able to explain our experimental data more accurately.

## ACKNOWLEDGEMENTS

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