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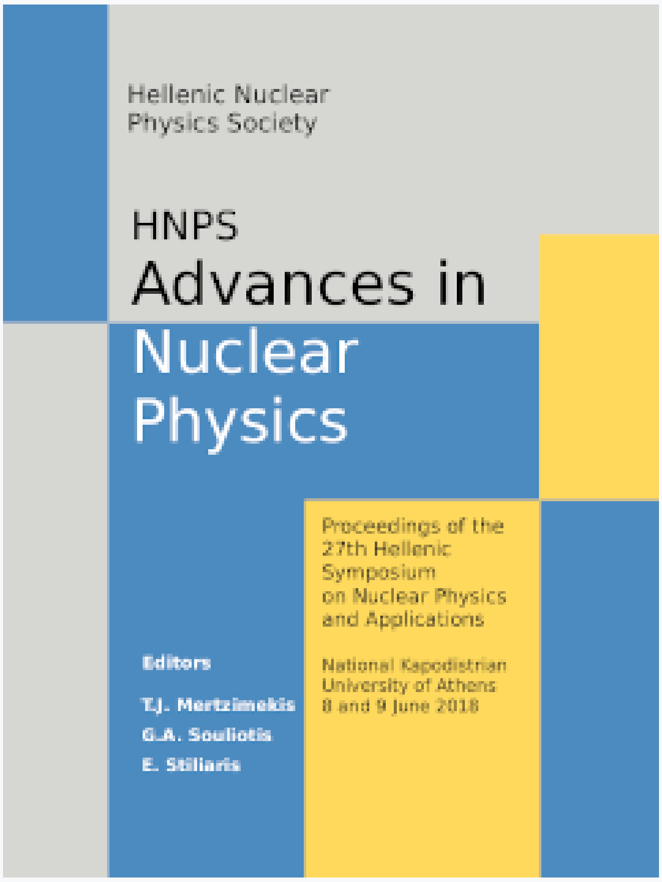

Production of C4+ (2s2p 3,1P) hollow states in collisions of 6-18 MeV C4+ (1s2, 1s2s 3S) mixed-state beams with gas targets

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Production of $C^{4+}(2s2p\ ^{3,1}P)$ 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 $^{3,1}P$ states from the metastable states 1s2s $^{3,1}S$ 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 $C^{4+}(2s2p\ ^{3,1}P) \rightarrow C^{5+}(1s) + e^-$ 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 $^{3,1}P$ 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 $^{3,1}P$ 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.

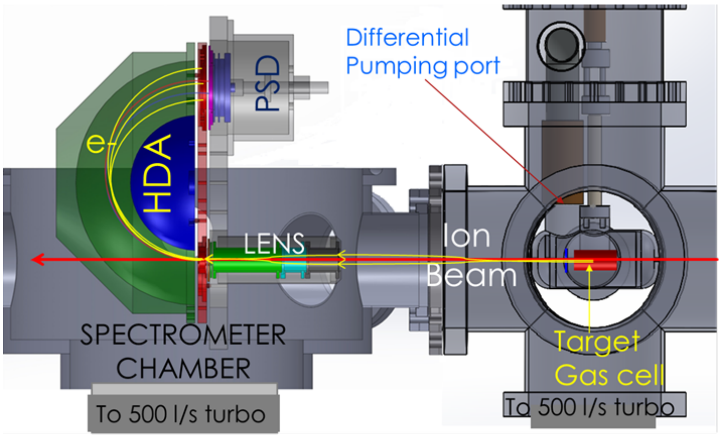

Fig. 1. The experimental apparatus used for zero-degree Auger projectile spectroscopy. From right to left, the ion beam (red horizontal arrow) passing through the gas cell colliding with the target gas and traverses the lens and HDA. Electrons from the resulting projectile autoionizing states, emitted 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 ($1s2s\ ^{3,1}S$) coexist. The percentage of each component in the mixture is determined from the way the ion beam is produced. In a tandem Van de Graff 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 ($1s2s\ ^{3,1}S$) 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 $2s2p\ ^{3,1}P$. 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 $2s2p\ ^{3,1}P$ states.

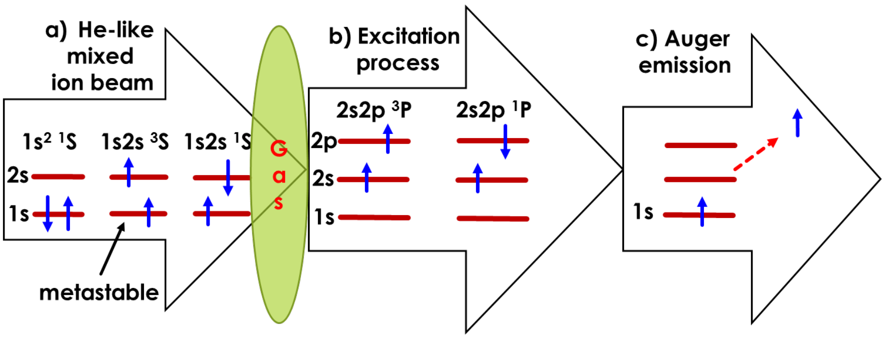

Fig. 2. a) The incident He-like beam comes in a mixture of three states, b) after the collision of the ion beam with the gas target, the projectile ion is excited to the 2s2p $^{3,1}P$ states, c) subsequently, the excited ion relaxes by Auger decay.

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 (~14%), compared to similar spectra obtained with a lower 1s2s ^3S fraction (~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.

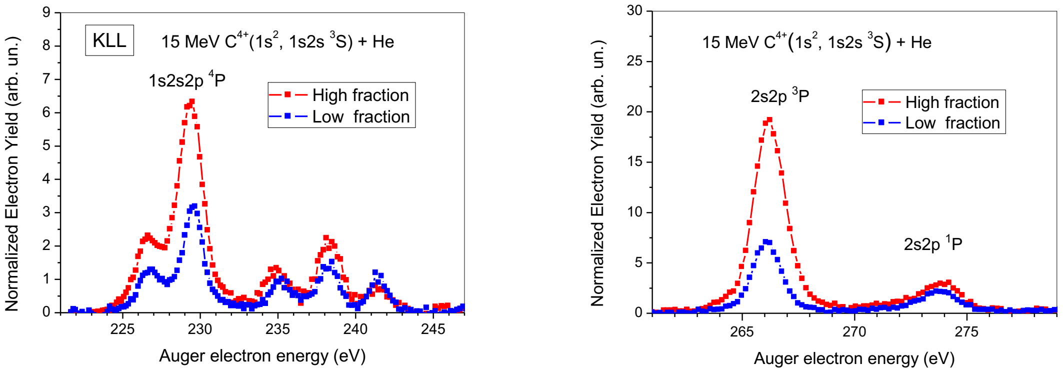

Fig. 3. Normalized zero-degree Auger electron KLL spectra produced in collisions of 15 MeV C^{4+} ions with either a high 1s2s ^3S metastable fraction (red line) or a lower fraction (blue line). The two spectra are different energy regions of the recorded KLL spectrum.

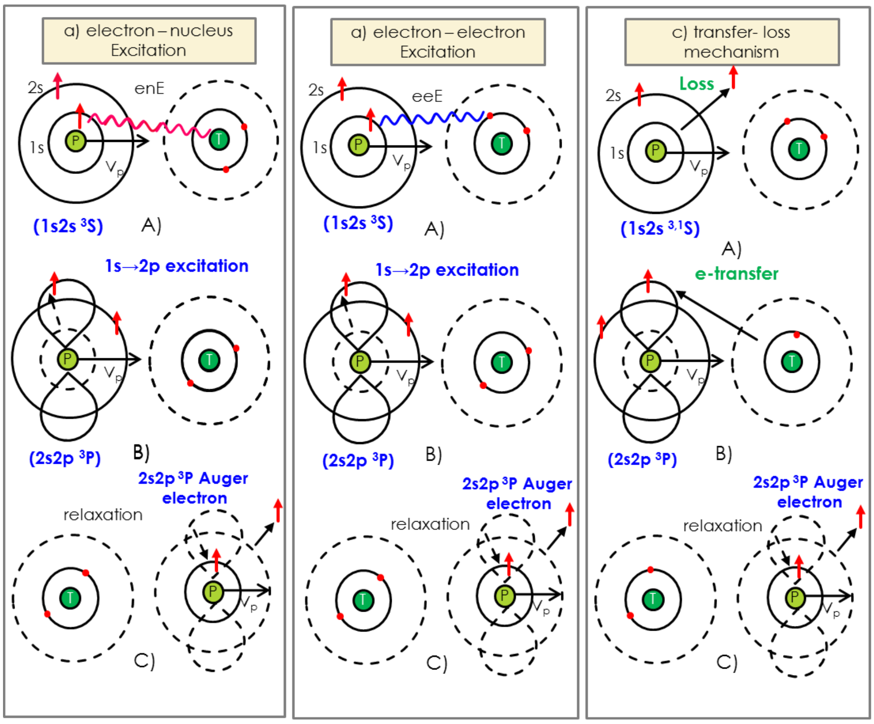

Fig. 4. Mechanisms leading to the production of the 2s2p ^{3}P state by single excitation of a core electron in the 1s2s ^{3}S initial state: a) Electron-nucleus excitation (enE) interaction, b) Electron-electron excitation (eeE) interaction, c) Transfer Loss (TL) mechanism Note that for the TL mechanism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

The potential formation mechanisms are shown in Fig. 4 and Fig. 5. For the 2s2p ^{3}P state we can safely assume that it can be primarily formed from 1s2s ^{3}S metastable state through 1s→2p single excitation by either electron-nucleus (e-n) or electron-electron (e-e) interaction. Secondary processes involving the 1s2s ^{3,1}S metastable states, such as transfer-loss (TL), where the ionization of a projectile electron (loss) occurs simultanesouly with the transfer of a target electron [4] are also possible, but with much lower probability. Contributions from the 1s2s ^{1}S 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 ^{3,1}P states needs further consideration. For example, the 2s2p ^{1}P state can be populated by direct 1s→2p single excitation from the 1s2s ^{1}S state, by double excitation from the ground state 1s^2 ^{1}S, by 1s→2p single excitation with exchange from the 1s2s ^{3}S or by TL from either the 1s2s ^{3}S or ^{1}S 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 ^{3}P increases with the energy reaching a maximum at around 12-15 MeV and then slightly decreases again, while for 2s2p ^{1}P the maximum occurs much earlier at 6 MeV from which the probability keeps droping with increasing collision energy. Concerning the 2s2p ^{3}P, this behavior can be explained by the dependence of the cross section of the 1s→2p excitation from the collision energy and the variation of the fraction of 1s2s ^{3,1}S of the ion beam which also depends on the projectile’s energy. For the 2s2p ^{1}P state production a smoother behavior is observed, possibly indicating a strong dependence from the 1s^2 ^{1}S ground state.

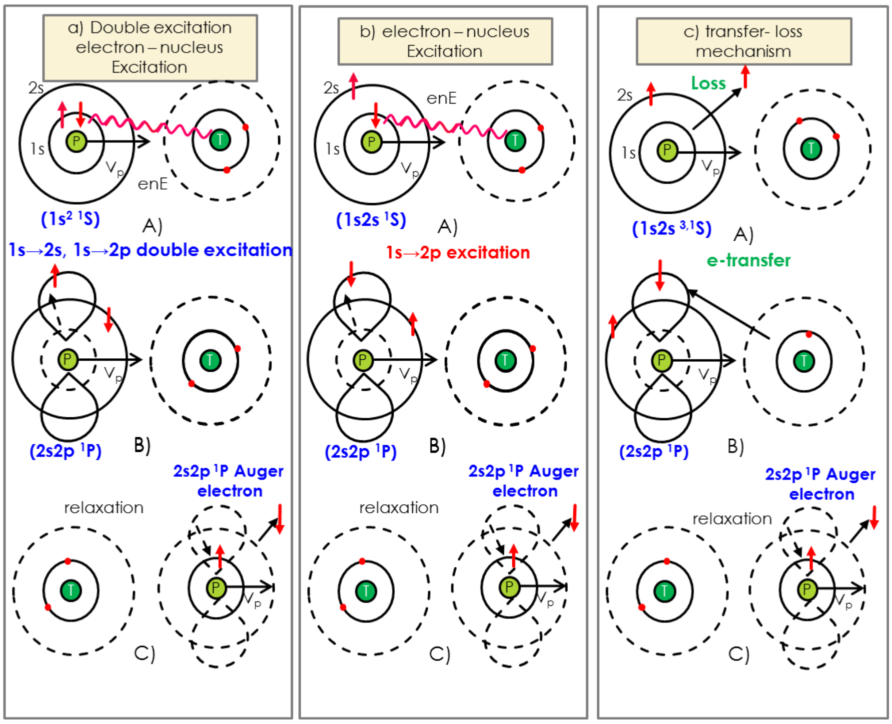

Fig. 5. Same as in Fig. 4, but for the 2s2p ^{1}P state: a) double enE from 1s^2 ^{1}S initial state, b) single enE from the 1s2s ^{1}S initial state, c) TL mechanism from either 1s2s ^{3}S or ^{1}S initial state.

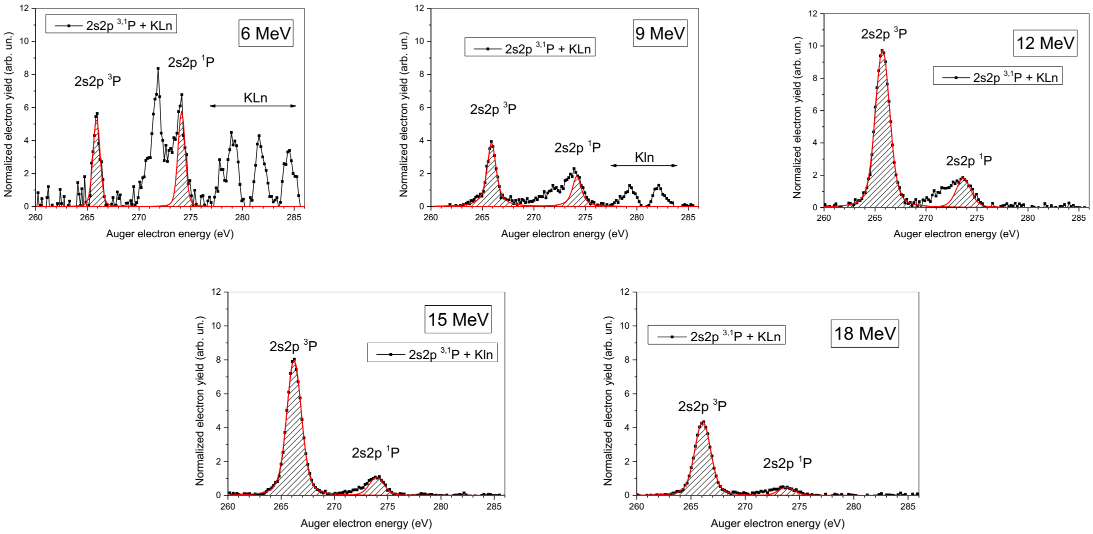

Fig. 6. Energy dependence of the 2s2p ^{3,1}P normalized yields. As the collision energy increases, the 2s2p ^{3}P yield increases reaching a maximum around 12-15 MeV and then decreases again, while the 2s2p ^{1}P yield gradually decreases from a maximum around 6 MeV. KLn Auger lines indicated are mostly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

CONCLUSIONS

In our experiments we used the naturally occurring mixed state ion beam of C^{4+} ($1s^2$, 1s2s $^{3,1}S$) in collisions with various gas targets (H_2, He, Ne, Ar) to investigate the production mechanisms of 2s2s $^{3,1}P$ doubly excited states. We have measured absolute electron yields of 2s2p $^{3,1}P$ 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.

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