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# High Resolution Auger Projectile Electron Spectroscopy of Li-like Ions Produced by Electron Capture in Collisions of He-like Ions with Gaseous Targets

Research Article

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**Abstract.** We have recently build a new experimental station with a beam line dedicated to atomic collision physics at the 5 MV TANDEM accelerator of the Institute of Nuclear and Particle Physics at the National Research Center "Demokritos" in Athens, Greece. A complete zero-degree Auger projectile spectroscopy apparatus composed of a single stage hemispherical spectrograph and a 2-dimensional position sensitive detector combined with a doubly differentially pumped gas target has been set up for high resolution studies of electrons emitted from projectile ions excited in collisions with target atoms. With the new setup we have started a systematic isoelectronic investigation of K-Auger spectra emitted from pre-excited ions in collisions with gas targets using novel techniques. Here, we present some of our first new results involving collisions of carbon He-like ions with target gases. These results are expected to lead to a deeper understanding of the neglected importance of cascade feeding of metastable states in collisions of ions with gas targets and further elucidate their role in the non-statistical production of excited three-electron states by electron capture, recently a field of conflicting interpretations awaiting further resolution.

**Keywords.** Electron capture; Ion-atom collisions; Zero-degree Auger projectile spectroscopy; Three-electron spin statistics; K-Auger spectra

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## 1. Introduction

High resolution Auger electron spectroscopy has become an important tool, over the last two decades, for obtaining information on both the atomic structure and the collision dynamics of multiple excited states produced in ion-atom collisions [1]. This interest has been generated to a large extent in the fields of thermonuclear fusion, hot plasmas, astrophysics, accelerator technology and basic physics of ion-atom collision dynamics. Accelerator-based atomic physics can now also be investigated for the first time in Greece through the APAPES project [2] in a new fully operational innovative electron spectroscopy apparatus [3]. Some of our first results are presented here.

## 2. Experimental Setup

The measurements were performed at the 5MV Tandem Van de Graaff accelerator of the Institute of Nuclear and Particle Physics (INPP), located at the National Center for Scientific Research (NCSR) "'Demokritos" in Athens Greece. A $C^{4+}$ ion beam was accelerated to energies of 12 and 18 MeV and then directed into a doubly differentially pumped gas cell that contained the gas targets Ne, He, Ar and $H_2$. The target pressure typically ranged from 5 to 20 mTorr to maintain single collision conditions. The $C^{4+}$ ion beam entering the gas cell target, as generated at the Tandem terminal foil stripper, contained a mixture of both ground ($1s^2\,{}^1S$) and metastable ($1s2s\,{}^3S$) states [4,5]. Auger electrons emitted at zero degrees with respect to the beam direction were energetically analyzed using a paracentric [6–10] hemispherical deflector analyzer (HDA) equipped with a 4-element focusing/deceleration entry lens and a 2-dimensional position sensitive detector (PSD) [11,12]. High resolution was achieved by pre-retarding the analyzed Auger electrons up to a deceleration factor of $F = 8$. Typically, $F = 4$ was enough to resolve the Li-like K-Auger lines presented here. Analyzed electron spectra were normalized to the number of ions collected in a Faraday cup (FC2) located at the exit behind the HDA. Beam currents at FC2 varied from 0.5 to 2 nA. In Figure 1, a schematic of the doubly differentially pumped target gas cell, the HDA, the 4-element input lens and the PSD inside the vacuum chamber can be seen.

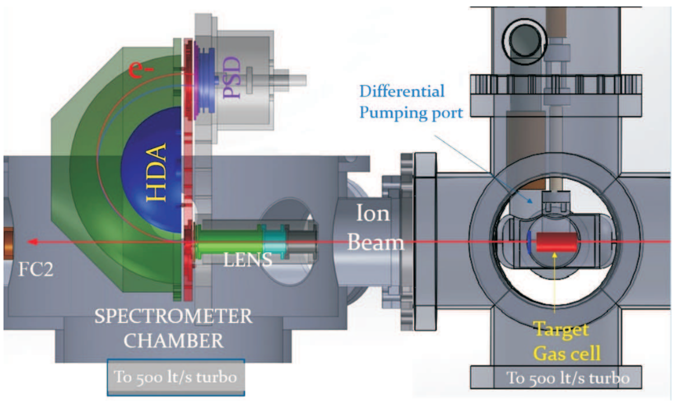


**Figure 1.** From right to left: Double differentially pumped target gas cell, 4-element injection lens, paracentric HDA with 2-D PSD and final Faraday Cup (FC2). The length of the target gas cell was $L_c = 49.9$ mm and the distance of its center to the lens entry $s_0 = 288.5$ mm

## 3. Single-electron Capture

Over the last 20 years there has been considerable interest in the atomic structure and dynamics of the production of multiply excited states using high resolution Auger electron spectroscopy. The recorded cross sections together with other information such as lifetimes and transition rates lead to a better understanding of the dominant processes at play. In the case of the production of the $1s2s2p\,^{2,4}P$ states observed in the Auger spectra during collisions of He-like ions with gas targets, it has been assumed that these lines are mostly produced by direct single electron capture into the $1s2s\,^3S$ component of the ion beam [13, 14]. However, more recently it has been shown that capture to higher lying $(1s2snl\,^{2,4}L_J)$ states should also be very probable and therefore cascade feeding of the $(1s2s2p\,^{2,4}L_J)$ can be expected to also occur [15–17]. As an example, for the case of $F^{7+}$ ions colliding with gas targets [15], the energy levels of the resulting $F^{6+}(1s2snl\,^{2,4}L_J)$ Li-like states, including dipole and Auger transition rates, for principal quantum numbers $2 \leq n \leq 5$ and $l = 0,\, n-1$ were calculated with the use of the well-known COWAN Hartree-Fock package. The energy level scheme along with the corresponding transition rates are displayed in Figure 2. As is evident, the doublets (Figure 2, right) Auger decay strongly to the K-shell, while the quartets (Figure 2, left) Auger decay much more weakly due to spin selection rules. E1 transition rates are of course the strongest for quartet to quartet and/or doublet to doublet transitions. Basic quantum mechanics requires the spin coupling of the $2p$ electron to the $1s2s\,^3S$ state yielding $1s2s2p\,^4P$ quartet and $1s2s2p$ $^2P$ doublet states to be in the ratio of $2:1$, i.e. $R = \sigma(1s2s2p\,^4P)/\sigma(1s2s2p\,^2P) = 2$, while the expected value of the ratio $R' = \sigma(1s2s2p\,^2P_+)/\sigma(1s2s2p\,^2P_-) = 3$ [18]. However, the values of $R$ extracted from the experimental measurements to date are typically much larger ranging in values of $R \sim 1-9$ [14–16]. This enhancement in $R$ has recently been theorized [15, 17] to be the result of radiative cascades dominantly feeding only the $^4P$ states, since the radiative branching ratios for transitions between quartets are found to be much larger than between doublets. This results in a selective enhancement of the lowest lying $^4P$ states in qualitative agreement with the experimentally observed enhancement in $R$. Alternatively, a new two-electron process termed the Pauli exchange interaction has also been proposed to explain the enhancement of the $^4P$ state production, without, however, any supporting theoretical calculation [16], to date.

Finally, it is important to mention, that the inherent long lifetime ($\sim ns$) of the $1s2s2p\,^4P_{1/2,3/2,5/2}$ metastable states leads to an additional difficulty in the quantitative analysis of the measured $^4P$ production cross section [13, 16, 19]. Indeed, in all these 0° measurements, the electron spectrometer lies in the direct path of the ion beam, and therefore the metastable projectile states decay all along the ionic projectile path towards and through the spectrometer. Thus, one has to correctly account both for the decay of these states along the path of observation on one hand, as well as for the increase of the spectrometer acceptance solid angle, as the emission point approaches the entry of the spectrometer, on the other. This can result in a considerable correction to the measured metastable electron yield. This correction has been treated in the literature, either in a purely geometrical approach [13, 16, 19] or very recently, for our measurements using an HDA with entry lens (as here), in a new Monte Carlo electron trajectory simulation approach within the well-known SIMION charged particle optics software [20]. In this later approach, kinematic effects, particular to Auger emission from fast moving projectile ions such as kinematic line broadening and solid angle limitations, are also

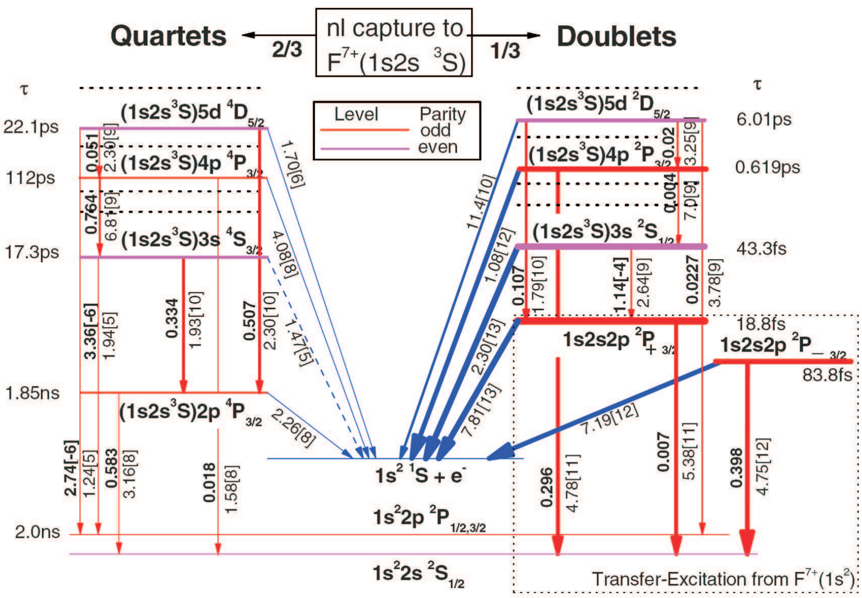


**Figure 2.** Li-like quartet and doublet $F^{6+}(1s2snl)$ energy level scheme (not to scale) resulting from single electron $nl$ capture to $F^{7+}(1s2s\,^3S)$ states. Only a few representative levels are indicated. Arrows represent transitions with widths roughly proportional to their strength: radiative E1 (dipole) vertical red lines and Auger slanted blue lines. Rates in $s^{-1}$ are given to the right of the arrows with the quantity in square brackets indicating powers of 10, while radiative transition branching ratios are given in bold to their left. Also indicated are total lifetimes, while dashed arrows represent Coulomb forbidden transitions (from ref. [15]).

included for the first time, allowing for a more accurate and realistic line shape modeling [21] of both metastable and prompt Auger lines.

## 4. New Experimental Results

Figure 3(a) and (b) show the Auger electron spectra obtained for 12 and 18 MeV $C^{4+}$ respectively mixed state $(1s^2, 1s2s^3S)$ ion beam, as generated at the Tandem accelerator terminal foil stripper, in collisions with four different gas targets. The energy scale of the spectra has been transformed from the laboratory frame to the projectile rest frame and the electron yield has been normalized to the beam current and target pressure so that the relative contributions of the various Auger lines can be compared. The spectra show five Auger lines with significant intensities in order of increasing electron energy: $1s2s^2\,^2S$, $1s2s2p\,^4P$, $1s2s2p\,^2P_-$, $1s2s2p\,^2P_+$ and $1s2p^2\,^2D$. All $1s2s2l$ states can be formed either from a single electron transfer to the $1s2s\,^3S$ state or (except for the $^4P$) by a two electron process involving a single electron transfer accompanied by simultaneous electronic $(1s \rightarrow 2l)$ electron excitation from the $1s^2$ ground state (transfer excitation or TE). TE is also expected to be predominantly responsible for the production of the $1s2p^2\,^2D$ state. In addition, as already mentioned, both cascade feeding as well as the Pauli exchange interaction [21] have been proposed to explain the enhancement of the $^4P$.

For the case of the 12 MeV $C^4+$ on Ne and He, our results can be directly compared with previously published experimental data [16]. While the overall spectra are very similar, there is an important difference in the intensity of the observed $^4P$ Auger line which is seen to be almost three times stronger in our case. A possible explanation for this seeming discrepancy, could be the five times greater distance of our HDA spectrometer from the target gas cell in our experimental set up in comparison with that of ref. [16], which also used the more traditional two-stage parallel plate slit analyzer. This increased distance could result in more ions decaying before reaching the spectrometer entry, thus leading to an effective increase of the observed intensity of the $^4P$ line. Finally, in Figure 3(c) we show the extracted ratios $R = \sigma(^4P)/\sigma(^2P)$ and $R' = \sigma(^2P_+)/\sigma(2P_-)$. The $^4P$ metastable Auger intensity was corrected for life time effects using our new SIMION Monte Carlo simulation approach [21, 22], while the TE corrections could be safely estimated only for our 12 MeV He and Ne measurements using the relative TE contributions previously measured in ref. [16]. The TE corrections required in the 18 MeV determination of $R$ and $R'$ must await further measurements with a ground state beam, which will only become possible when the gas terminal stripper is also installed.

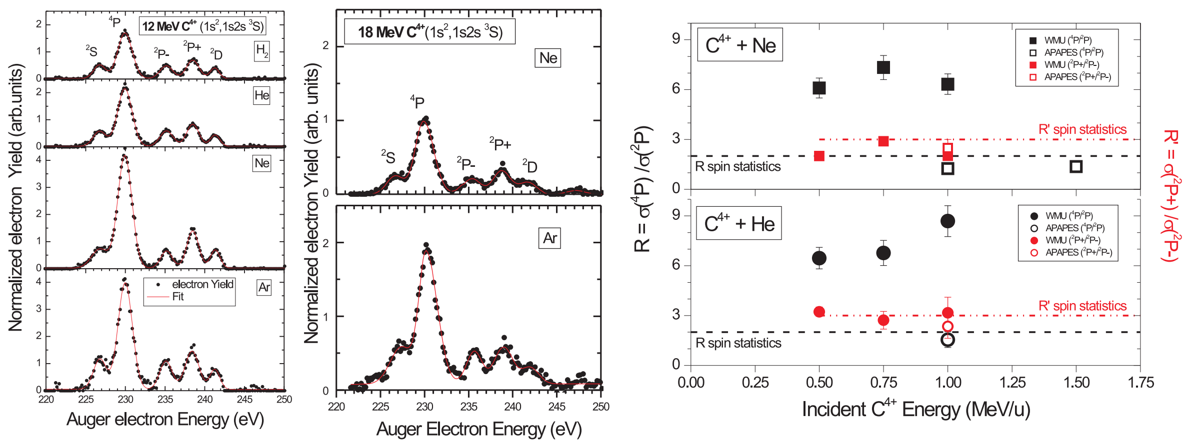


**Figure 3.** (a) Measured zero-degree Auger emission spectra for 12 MeV $C^{4+}$ mixed beam $(1s^2, 1s2s\,^3S)$ state in collisions with Ne, He, $H_2$ and Ar. The resulting Auger lines have been identified as belonging to the three-electron electron states $1s2l2l'\,^{2,4}L$ indicated. The spectra have been transformed to the rest frame of the projectile and the electron yield has been normalized to the incident beam current and gas pressure. (b) As in (a) but for 18 MeV $C^{4+}$ beam in collisions with Ne and Ar gas targets. (c) Experimentally determined ratios (left scale) for $R = \sigma(^4P)/\sigma(^2P_+ + {}^2P_-)$ and (right scale in red) for $R' = \sigma(^2P_+)/\sigma(^2P_-)$ of the production cross sections of (a) and (b). Also shown for comparison are the results of the previously published experimental data from WMU [16]. Corrections for both the $1s2s2p\,^4P$ life time effects and TE have also been included.

## 5. Summary and Conclusions

It is obvious from Figure 3(c), that the already published [16] values for $R$ are approximately 2-4 times higher than our new results depending on the target. For the case of the $R'$ ratio though, fairly good agreement is found with the expected spin recoupling value of 3 for both of our new results as well as those of ref. [16] (not shown). Our new results, even though much closer to the spin statistics direct $2p$ capture value of 2, are now seem to be a bit too low to also accommodate the expected cascade contributions already mentioned [15–17]. This rather puzzling state of affairs clearly needs further investigation. We plan to continue with our systematic experimental investigation of these ratios for all first row He-like ion beam in collisions with various targets, as well as with a theoretical treatment of electron capture, cascade feeding and the problem of the determination of the correction factor relevant to our measurements. We shall also soon have available both a terminal gas stripper which will allow for the production of pure ground state He-like beams from which we can also determine the necessary TE corrections, as well as a foil and gas post stripper, which will allow us to vary the available mixture of ground to metastable ion beam composition, further testing the self-consistency of our overall analysis.

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### Competing Interests

The authors declare that they have no competing interests.

### Authors' Contributions

All the authors contributed significantly in writing this article. The authors read and approved the final manuscript.

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