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Κατασκευή τριών απογυμνωτών δέσμης για την παραγωγή ψηλά φορτισμένων ιόντων στον επιταχυντή TANDEM του Δημόκριτου

Μεταπτυχιακή εργασία

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Περιεχόμενα

1 Επιταχυντές Van de Graaff **7**

1.1 Η γεννήτρια Van de Graaff 7

1.1.1 Η αρχή λειτουργίας της γεννήτριας Van de Graaff 7

1.1.2 Βασικά χαρακτηριστικά και αρχές λειτουργίας επιταχυντών τύπου Tandem Van de Graaff. 9

1.2 Η τεχνική της απογύμνωσης ιόντων 10

1.2.1 Μηχανισμοί ανταλλαγής φορτίου κατά την κρούση ιόντων - ατόμων. 11

2 Η πρωτοβουλία της πειραματικής ομάδας του APAPES **15**

2.1 Εισαγωγή 15

2.2 Φασματοσκοπία ηλεκτρονίων ιόντων δέσμης 15

2.3 Τα κύρια μέρη της πειραματικής διάταξης του APAPES 17

2.4 Το κελί του αερίου στόχου 18

2.4.1 Η διαφορική άντληση του κενού 18

2.4.2 Η παροχή του κελιού με το αέριο- στόχο 19

2.4.3 Η ανάγκη κατασκευής μιας νέας βάσης ευθυγράμμισης 21

2.4.4 Η νέα βάση ευθυγράμμισης 22

2.5 Το φασματόμετρο ηλεκτρονίων 22

2.6 Ο ανιχνευτής 23

3 Απογύμνωση ιόντων **26**

3.1 Εισαγωγή 26

3.2 Θεωρητικές μελέτες 27

3.3 Ενεργές διατομές παραγωγής καταστάσεων φορτίου 27

3.4 Ημι-εμπειρικές μέθοδοι προσδιορισμού καταστάσεων στην απογύμνωση ιόντων 28

3.5 Η ανάγκη για έναν μετα-απογυμνωτή ηλεκτρονίων 30

3.6 Ο απογυμνωτής ηλεκτρονίων φύλλων άνθρακα ιόντων δέσμης. 30

3.7 Ο απογυμνωτής ηλεκτρονίων αερίου ιόντων δέσμης. 30

4 Φασματοσκοπία ηλεκτρονίων Auger ιόντων δέσμης ηλιοειδών ατόμων **36**

4.1 Φάσμα ηλεκτρονίων Auger C^{4+} + Ne 36

4.2 Παραγωγή της κατάστασης C^{4+} με χρήση απογυμνωτή ηλεκτρονίων φύλλου άνθρακα και αερίου N_2 36

Παραρτήματα **40**

Α΄ Μηχανολογικά σχέδια **41**

Β΄ Διεθνείς δημοσιεύσεις **64**

Β΄.1 Άρθρα σε επιστημονικά περιοδικά 64

Β΄.2 Συμμετοχές σε διεθνή συνέδρια 77

Κατάλογος Σχημάτων

1.1 Van de Graaff generator 8
1.2 Ο επιταχυντής του Ε.Κ.Ε.Φ.Ε Δημόκριτος 9
1.3 Το δωμάτιο του επιταχυντή 9
1.4 Το τερματικό 10
1.5 Οι δύο τεχνικές απογύμνωσης ιόντων δέσμης 11
1.6 Μηχανισμοί ανταλλαγής φορτίου σύμφωνα με τον H.D. Betz 12
1.7 Ο Μηχανισμός δέσμευσης ηλεκτρονίου με ταυτόχρονη εκπομπή ακτινοβολίας 13
1.8 Μηχανισμοί δημιουργίας και συμπλήρωσης οπών 14
1.9 Μηχανισμοί διέγερσης και αποδιέγερσης ηλεκτρονίων 14

2.1 Τυπικά φάσματα ανθρακα φασματοσκοπίας ηλεκτρονίων ιόντων δέσμης . 16
2.2 Το σύστημα στόχου, αναλυτή, ανιχνευτή 17
2.3 Η δημιουργία της πειραματικής γραμμής $L45$ του APAPES 18
2.4 Η πειραματική γραμμή $L45$ του APAPES 18
2.5 Το κελί αερίου στόχου 19
2.6 Η διαφορική άντληση του αερίου 20
2.7 Το σύστημα σταθεροποίησης πίεσης αερίου στόχου 21
2.8 Το σύστημα παροχής των αερίων στόχου 21
2.9 Γεωμετρική μελέτη των συνθηκών ευθυγράμμισης του στόχου 22
2.10 Το σύστημα βάσης ευθυγράμμισης-στόχου 23
2.11 Μηχανολογικό σχέδιο της βάσης ευθυγράμμισης 23
2.12 Η νέα βάση ευθυγράμμισης 24
2.13 Το φασματόμετρο 24
2.14 Ο μηχανισμός των δυνόδων 25
2.15 Ο πολυκαναλικός ανιχνευτής 25

3.1 Διάγραμμα πιθανοτήτων παραγωγής καταστάσεων φορτίου σύμφωνα με τον ημι-εμπειρικό τύπου του R.O. Sayer 29
3.2 Δημιουργία της κατάστασης O^{6+} 30
3.3 Δημιουργία της κατάστασης F^{7+} 31
3.4 Δημιουργία της κατάστασης B^{3+} 31
3.5 Δημιουργία της κατάστασης B^{3+} 32
3.6 Το σύστημα των απογυμνωτών ηλεκτρονίων 32

3.7 Σχέδια του απογυμνωτή ηλεκτρονίων αερίου 33
3.8 Μηχανολογικό σχέδιο του αέριου απογυμνωτή ηλεκτρονίων 34
3.9 Εργασίες εγκατάστασης 34
3.10 Το σημείο των απογυμνωτών ηλεκτρονίων 35
3.11 Ο απογυμνωτής ηλεκτρονίων ιόντων δέσμης φύλλων άνθρακα 35
3.12 Ο απογυμνωτής ηλεκτρονίων αερίου ιόντων δέσμης 35

4.1 Υπολογισμός των πιθανοτήτων παραγωγής της κατάστασης C^{4+} με διαφορετικές μεθόδους απογύμνωσης 37
4.2 Φάσμα ηλεκτρονίων 12 MeV C^{4+} + Ne 38
4.3 Φάσμα ηλεκτρονίων 12 MeV C^{4+} + He 38

Πρόλογος

Η παρούσα διπλωματική εργασία εκπονήθηκε στα πλαίσια μεταπτυχιακών σπουδών στο Μεταπτυχιακό Δίπλωμα Ειδίκευσης "Φυσική και τεχνολογικές εφαρμογές" της Σχολής Εφαρμοσμένων Μαθηματικών και Φυσικών Επιστημών του Ε.Μ.Π. Η εργασία σχεδόν στο σύνολό της πραγματοποιήθηκε στον επιταχυντή Tandem Van de Graaff του Ινστιτούτου Πυρηνικής και Σωματιδιακής Φυσικής του Ε.Κ.Ε.Φ.Ε "Δημόκριτος" κατά την περίοδο Ιούλιος 2014 - Σεπτέμβριος 2015 υπό την επιστημονική επίβλεψη του καθηγητή του Τμήματος Φυσικής του Πανεπιστημίου Κρήτης κ. Θεόδωρο Τζούρο, και την ακαδημαϊκή επίβλεψη του αναπληρωτή καθηγητή του Τμήματος Φυσικής της Σχολής Εφαρμοσμένων Μαθηματικών και Φυσικών Επιστημών του Ε.Μ.Π κ. Μιχάλη Κόκκορη. Η παρούσα εργασία περιγράφει τον σχεδιασμό, την κατασκευή και τη λειτουργία δυο απαραίτητων βελτιωτικών συστημάτων για την πειραματική πρωτοβουλία του ερευνητικού προγράμματος APAPES: α) Μια νέα βάση στήριξης για την ακριβέστερη ευθυγράμμιση του κελιού του αερίου στόχου και β) ένα απογυμνωτή ηλεκτρονίων αερίου, που εγκαταστάθηκε μεταξύ του μαγνήτη ανάλυσης και του μαγνήτη επιλογής πειραματικής γραμμής του επιταχυντή. Επίσης παρατίθενται και πειραματικά αποτελέσματα με την συνεισφορά των δύο αυτών νέων συστημάτων. Η πειραματική ομάδα του APAPES, (Ατομική Φυσική με Επιταχυντές: Φασματοσκοπία Ηλεκτρονίων Ιόντων Δέσμης) είναι η πρώτη στην Ελλάδα που χρησιμοποιεί επιταχυντές για έρευνα στον τομέα της ατομικής φυσικής. Το ερευνητικό πρόγραμμα πραγματοποιήθηκε υπό την εποπτεία και την καθοδήγηση του καθηγητή του Τμήματος Φυσικής του Πανεπιστημίου Κρήτης κ. Θεόδωρο Τζούρο.

Abstract

The basic aim of this work is to describe in detail the design, construction and implementation of two novel systems for improving the APAPES experimental line: a) A new translation stage for the target gas cell where the collisions between the ion beam and target gas take place, and b) a gas post stripper installed in the beam line between the analyzing and switching magnets of the "Demokritos" Tandem Van de Graaff accelerator. The APAPES (i.e. Atomic Physics with Accelerators, Projectile Electron Spectroscopy) initiative is the first research project in Greece to use accelerators for atomic physics research. Its goal is to perform measurements of the excitation of the projectile ion using high resolution Auger electron spectrometry. This thesis is a contribution to the whole project. In this thesis both a theoretical and an experimental approach to ion stripping is presented, along with a comparison between terminal and post stripping for both foil and gas stripping. The whole project was completed at the National Center for Science and Research "Demokritos" in the Institute of Nuclear and Particle Physics in Athens, Greece, under the supervision of Professor of the University of Crete, Mr. Theo Zouros.

Κεφάλαιο 1

Επιταχυντές Van de Graaff

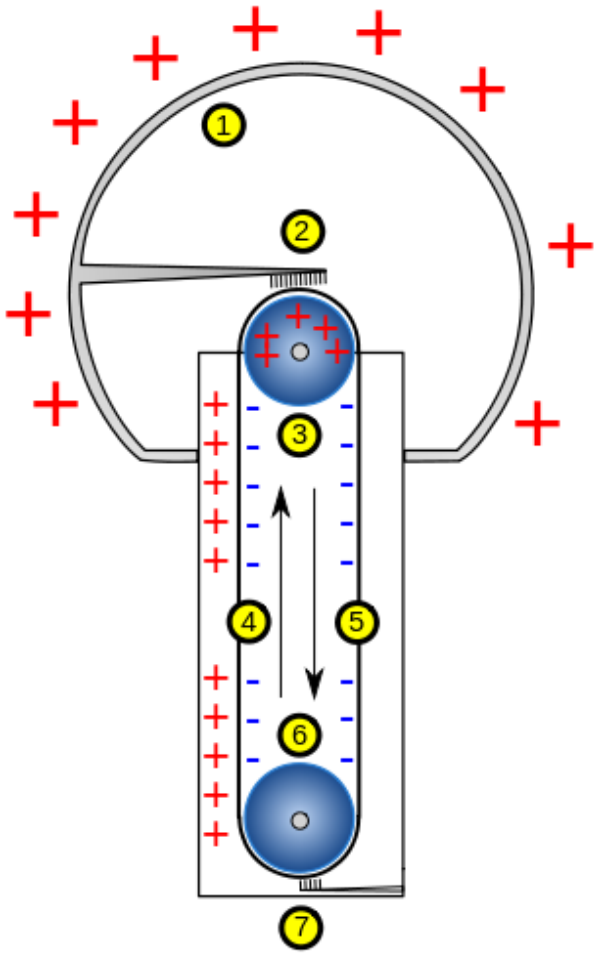
1.1 Η γεννήτρια Van de Graaff

Ο Αμερικανός φυσικός, Dr Robert Jemison Van de Graaff επινόησε την γεννήτρια Van de Graaff το 1931. Η συσκευή αυτή έχει την δυνατότητα να παράγει εξαιρετικά υψηλές τάσεις. Αρχικά ήταν ικανή να παράγει τάσεις μέχρι περίπου 1 εκατομμύριο Volts. Στις μέρες μας γεννήτριες Van de Graaff που χρησιμοποιούνται σε επιταχυντές μπορούν να παράγουν τάσεις μέχρι 20 εκατομμύρια Volts. Ο Van de Graaff επινόησε την γεννήτρια για να παρέχει την απαιτούμενη ενέργεια που χρειάζονταν για τους πρώιμους επιταχυντές σωματιδίων. Αυτοί οι επιταχυντές, γνωστοί και ως επιταχυντές Van de Graaff, χρησιμοποιούνται ακόμα και σήμερα σε πειράματα πυρηνικής και ατομικής φυσικής [1].

1.1.1 Η αρχή λειτουργίας της γεννήτριας Van de Graaff

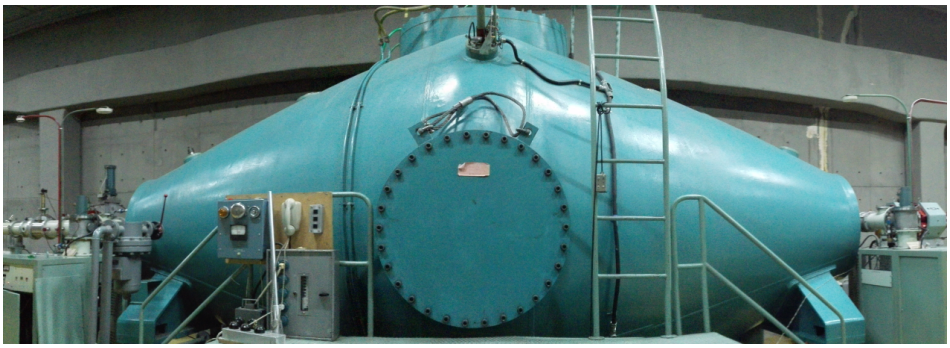
Το σύστημα της γεννήτριας αποτελείται από μια μεγάλη μεταλλική σφαίρα τοποθετημένη πάνω σε στέρεες στήλες μονωτικού υλικού, συνήθως γυαλιού. Ένας ιμάντας φτιαγμένος από μονωτικό υλικό κινείται εφαπτόμενος σε δύο κυλίνδρους (3) και (6). Ο κύλινδρος (3) βρίσκεται στο κέντρο της μεταλλικής σφαίρας ενώ ο (6) είναι κατακόρυφος με τον (3) και βρίσκεται στο κάτω μέρος του επιταχυντή. Οι δύο κύλινδροι περιστρέφονται με την βοήθεια ενός μοτέρ και κινούν συνεχώς τον ιμάντα. Στα σημεία (2) και (7) είναι δύο μεταλλικές "χτένες" οι οποίες ονομάζονται "collecting combs".

Το θετικό τερματικό μιας πηγής υψηλής τάσης είναι συνδεδεμένο με τον κόμβο (7). Εκεί δημιουργούνται φορτία τα οποία συγκεντρώνονται στις άκρες της μεταλλικής "χτένας". Το ηλεκτρικό πεδίο εκεί αυξάνει και ιονίζει τον αέρα κοντά. Τα θετικά φορτία απωθούνται και εναποτίθενται στο ιμάντα λόγω του φαινομένου "corona discharge". Τα φορτία μεταφέρονται με τον ιμάντα προς τα πάνω καθώς κινείται. Όταν το θετικά φορτισμένο κομμάτι του ιμάντα έρθει μπροστά από την "χτένα" (2), τα φορτία μεταφέρονται στην μεταλλική σφαίρα (1) η οποία φορτίζεται θετικά. Τα θετικά φορτία κατανέμονται ομοιόμορφα στην επιφάνεια της σφαίρας όπως συμβαίνει σε όλους τους αγωγούς. Η

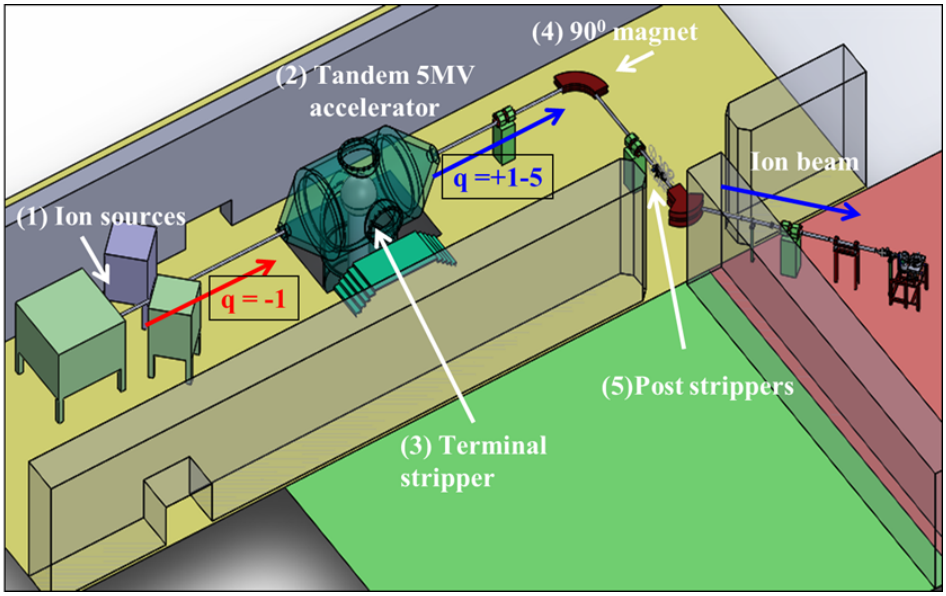


Σχήμα 1.1: Τα βασικά μέρη της γεννήτριας Van de Graaff.

διαδικασία αυτή επαναλαμβάνεται με το αφόρτιστο κομμάτι του ιμάντα να επιστρέφει κάτω, να συλλέγει θετικό φορτίο από το (7) και το οποίο στην συνέχεια, καθώς μεταφέρεται προς τα πάνω, συλλέγεται από το (2). Όλο και περισσότερο θετικό φορτίο συγκεντρώνεται στην σφαίρα, αυξάνοντας την τιμή του δυναμικού της μέχρι ένα μέγιστο το οποίο εξαρτάται από την επιφάνεια της. Εάν το δυναμικό αυξηθεί περαιτέρω, η μονωτική ικανότητα του αερίου μέσα στο οποίο βρίσκεται όλο το σύστημα καταρρέει και η σφαίρα εκφορτίζεται. Η κατάρρευση αυτή συμβαίνει εντός ενός θαλάμου από ατσάλι γεμάτου με SF6 σε πίεση 5atm με σκοπό να αποτρέπονται τέτοια συμβάντα [1], [2].



Σχήμα 1.2: Ο Επιταχυντής του Ε.Κ.Ε.Φ.Ε "Δημόκριτος".

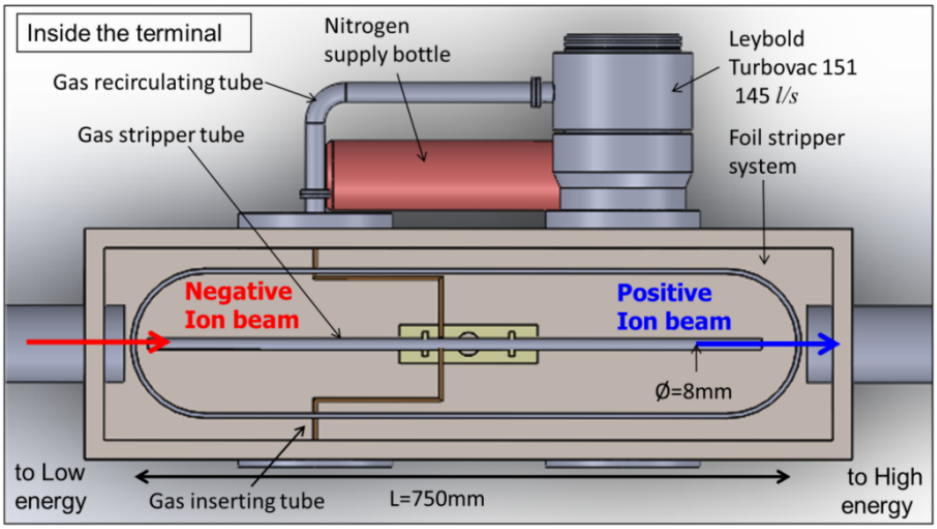


Σχήμα 1.3: Γραφική απεικόνιση του δωματίου του επιταχυντή και των δωματίων πειραμάτων του Ινστιτούτου Επιταχυντή του Ε.Κ.Ε.Φ.Ε "Δημόκριτος".

1.1.2 Βασικά χαρακτηριστικά και αρχές λειτουργίας επιταχυντών τύπου Tandem Van de Graaff.

Οι επιταχυντές Van de Graaff βασίζονται στην ηλεκτροστατική έλξη ή άπωση μεταξύ ετερόσημα ή ομόσημα φορτισμένων σωμάτων. Τα αρνητικά ιόντα που δημιουργούνται στην πηγή (Q =-1) έλκονται από την θετικά φορτισμένη σφαίρα και επιταχύνονται κερδίζοντας ενέργεια $E = VQ$. Στην συνέχεια διέρχονται μέσα από μέσο στο τερματικό του επιταχυντή με το οποίο συγκρούονται και το φορτίο τους διαφοροποιείται. Στην περίπτωση που το φορτίο του ιόντος παραμείνει $Q = -1$, όση ενέργεια κέρδισε κατά την προσέγγισή του στην σφαίρα θα χαθεί σταδιακά, και θα εξέλθει του επιταχυντή με την αρχική ενέργεια E_0 που είχε κατά την προεπιτάχυνση του στην πηγή. Στην περίπτωση που το ιόν χάσει ένα ηλεκτρόνιο θα μετατραπεί σε ουδέτερο και η ενέργεια με

την οποία θα εξέλθει από τον επιταχυντή είναι $E = E_0 + VQ$. Τέλος, στην περίπτωση που το ιόν χάσει παραπάνω από ένα ηλεκτρόνιο θα μετατραπεί σε θετικό ιόν και θα επιταχυνθεί περαιτέρω αναλόγως του τελικού φορτίου του ιόντος σύμφωνα με τον τύπο $E = E_0 + V(Q + 1)$. Οι μηχανισμοί ανταλλαγής φορτίου κατά την κρούση ιόντων - ατόμων περιγράφονται με μεγαλύτερη λεπτομέρεια παρακάτω. Στην συνέχεια το επιθυμητό ιόν και η αντίστοιχη ενέργεια επιλέγεται, καθώς το σύνολο της δέσμης διέρχεται μέσα από έναν μαγνήτη ανάλυσης (analyzing magnet) ο οποίος έχει το απαιτούμενο μαγνητικό πεδίο, έτσι ώστε να περάσει μόνο η επιθυμητή κατάσταση, αποκόπτοντας τις υπόλοιπες οι οποίες διαγράφουν τροχιές διαφορετικής καμπυλότητας.

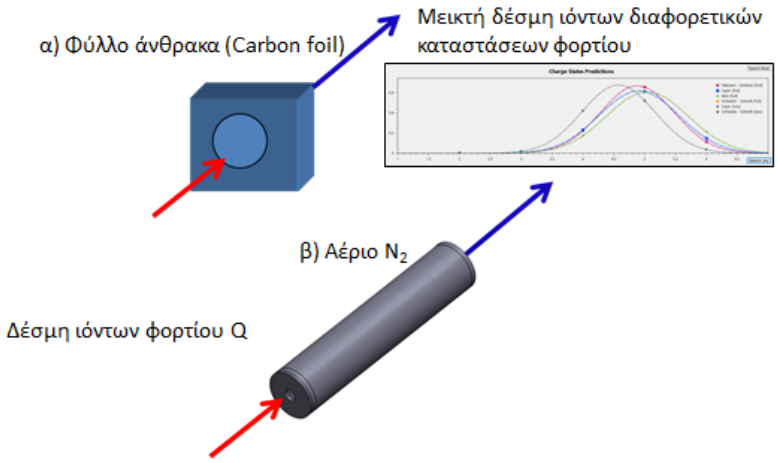


Σχήμα 1.4: Το τερματικό ενός τυπικού επιταχυντή Tandem Van de Graaff.

1.2 Η τεχνική της απογύμνωσης ιόντων

Η τεχνική της απογύμνωσης ιόντων χρησιμοποιείται στους επιταχυντές τύπου Tandem Van de Graaff για την επίτευξη δύο σταδίων επιτάχυνσης των ιόντων. Όταν ένα επιταχυνόμενο ιόν εισέρχεται στο τερματικό του επιταχυντή, θα διέλθει μέσα από ένα υλικό, στερεό ή αέριο, με το οποίο είναι πιθανό να πραγματοποιήσει κρούσεις και πιθανότατα να χάσει ένα η περισσότερα ηλεκτρόνια. Στην περίπτωση που το τελικό φορτίο του ιόντος είναι θετικό, θα επιταχυνθεί περαιτέρω λόγω της απωστικής δύναμης που του ασκείται από την θετικά φορτισμένη σφαίρα στο κέντρο του επιταχυντή. Χωρίς αυτήν την τεχνική το φορτίο του ιόντος θα παρέμενε $Q = -1$ με αποτέλεσμα όση ενέργεια κερδίσει κατά την προσέγγιση του στο κέντρο της θετικά φορτισμένης σφαίρας, να το χάσει κατά την απομάκρυνσή του από αυτή.

Στο σχ. 1.4 μπορούμε να δούμε μια σχηματική απεικόνιση ενός τερματικού επιταχυντή τύπου Tandem Van de Graaff. Το συγκεκριμένο σχήμα αναπαριστά το τερματικό του επιταχυντή του Ε.Κ.Ε.Φ.Ε "Δημόκριτος" ύστερα από την πιο πρόσφατη προσθήκη



Σχήμα 1.5: Η τεχνική της απογύμνωσης ιόντων δέσμης α) με φύλλο άνθρακα και β) με αέριο.

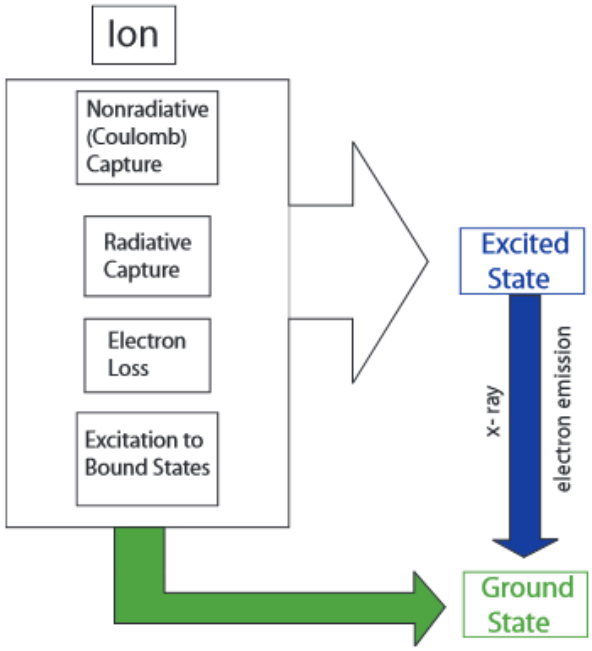
ενός απογυμνωτή ηλεκτρονίων αερίου συνοδευόμενο από ένα σύστημα ανακύκλωσης αερίου. Μια σχηματική αναπαράσταση των δύο μεθόδων απογύμνωσης της δέσμης ιόντων φαίνεται στο σχ. 1.5.

1.2.1 Μηχανισμοί ανταλλαγής φορτίου κατά την κρούση ιόντων - ατόμων.

Όταν ταχέως κινούμενα ιόντα διέρχονται μέσα από κάποιο υλικό το φορτίο τους διαφοροποιείται λόγω δέσμευσης ή απώλειας ηλεκτρονίων, δημιουργώντας μια δυναμικά σταθερή κατανομή φορτισμένων καταστάσεων χωρίς να επηρεάζεται η ταχύτητα των ιόντων. Η κατανομή αυτών των καταστάσεων διαμορφώνεται σύμφωνα με την ενεργό διατομή των μηχανισμών απώλειας ή δέσμευσης ηλεκτρονίων.

Οι πιο βασικές διαδικασίες ανταλλαγής φορτίου σε ατομικές κρούσεις είναι η δέσμευση ή η απώλεια ηλεκτρονίων. Όταν ένα ιόν με φορτίο Q συγκρουστεί με ένα άτομο, διάφορες διαδικασίες μπορούν να συμβούν οι οποίες θα αλλάξουν το φορτίο του ιόντος σε Q'. Στο σχ. 1.6 φαίνονται οι διαφορετικές διαδικασίες που μπορούν να συμβούν σε ένα ή περισσότερα ηλεκτρόνια κατά την κρούση ιόντων με άτομα σύμφωνα με τον H. D. Betz [3], [4].

1. Δέσμευση ηλεκτρονίου χωρίς ταυτόχρονη εκπομπή ακτινοβολίας (Nonradiative Electron Capture):
   Το ιόν δεσμεύει ένα η περισσότερα δέσμια ηλεκτρόνια από το άτομο-στόχο στην βασική ή σε κάποια διεγερμένη κατάσταση. Τα ελεύθερα ηλεκτρόνια υπόκεινται σε περιορισμούς που βασίζονται στην ορμή και την ενέργεια. Εάν ένα ηλεκτρόνιο μεταφερθεί από ένα άτομο του στόχου σε ένα ταχέα κινούμενο ιόν, το ηλεκτρόνιο

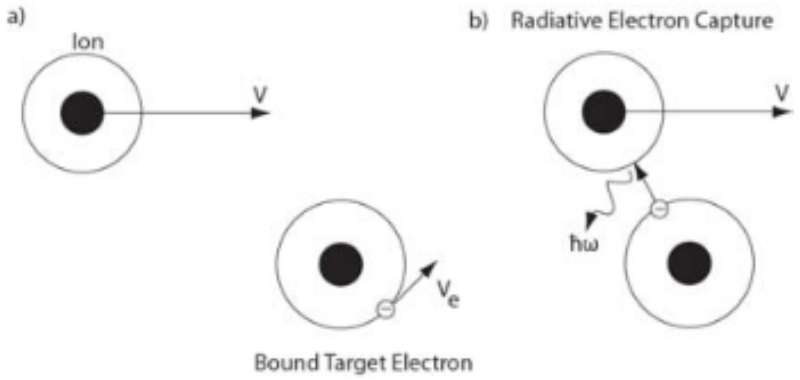


Σχήμα 1.6: Οι διαδικασίες που ο H.D. Betz [4], [3] θεώρησε ως θεμελιώδεις μηχανισμούς ανταλλαγής φορτίου.

πρέπει να έχει συνιστώσες ορμής τέτοιες που να είναι αντίστοιχες και να ταιριάζουν την υψηλή ορμή της δέσμης ιόντων [5].

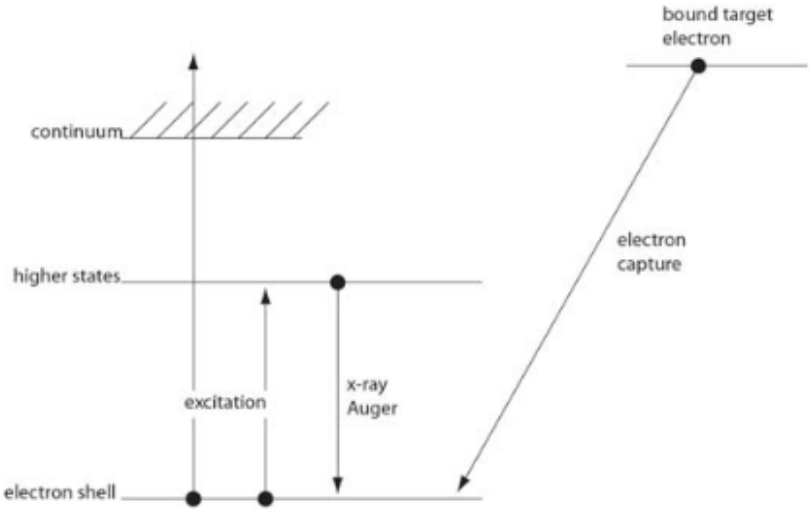
2. Δέσμευση ηλεκτρονίου με ταυτόχρονη εκπομπή ακτινοβολίας:
   Το ιόν δεσμεύει ένα ελεύθερο ή δέσμιο ηλεκτρόνιο στην βασική ή σε κάποια διεγερμένη κατάσταση συνοδευόμενο με ταυτόχρονη εκπομπή ενός φωτονίου βλ.σχ. 1.7. Αυτή η ανταγωνιστική διαδικασία δέσμευσης ηλεκτρονίου δεν έχει περιορισμούς στην ορμή και την ενέργεια μιας και η εκπομπή του φωτονίου δρα ως ένα τρίτο σώμα το οποίο μεταφέρει μακριά ενέργεια και ορμή, ταιριάζοντας τις παραμέτρους που απαιτούνται για την δέσμευση του ηλεκτρονίου [5].

3. Διέγερση στο συνεχές του φάσματος:
   Το ιόν χάνει ένα ή περισσότερα ηλεκτρόνια, αφήνοντας το ιόν στην βασική ή σε κάποια διεγερμένη κατάσταση. Ιόντα τα οποία έχουν μόνο ένα διεγερμένο ηλεκτρόνιο επιστρέφουν συνήθως γρήγορα στην θεμελιώδη κατάσταση, ωστόσο μετασταθείς καταστάσεις οι οποίες έχουν μεγάλους χρόνους ζωής μπορούν να παραχθούν. Υπάρχει μια συγκεκριμένη πιθανότητα τα ιόντα να είναι ακόμα διεγερμένα όταν μια επόμενη κρούση συμβαίνει. Έτσι ένα ιόν το οποίο έχει μείνει σε διεγερμένη κατάσταση μπορεί να αποδιεγερθεί μέσω εκπομπής Auger, προκαλώντας ιονισμό σε δεύτερο χρόνο από την κρούση. Το φαινόμενο Auger είναι

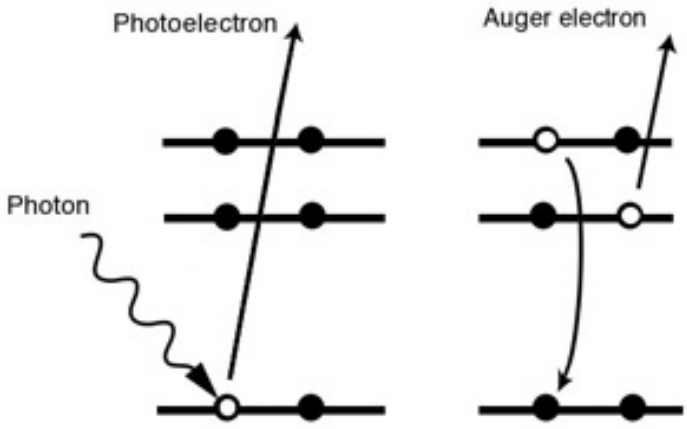


Σχήμα 1.7: Ο Μηχανισμός δέσμευσης ηλεκτρονίου με ταυτόχρονη εκπομπή ακτινοβολίας.

μεταφορά ενός ηλεκτρονίου από υψηλότερη ενεργειακή στάθμη σε μία χαμηλότερη, για την συμπλήρωση κάποιας οπής, όπου η περίσσεια ενέργεια μπορεί να αποβληθεί μέσω της εκπομπής ενός ηλεκτρονίου όπως φαίνεται στο σχ. 1.9 [5].



Σχήμα 1.8: Δημιουργία και συμπλήρωση μιας οπής εσωτερικής στοιβάδας με δέσμευση ενός ηλεκτρονίου από το στόχο.



Σχήμα 1.9: Οι δύο μηχανισμοί διέγερσης ενός ηλεκτρονίου στο συνεχές του φάσματος α) με αλληλεπίδραση με φωτόνιο και β) με αλληλεπίδραση δυο ηλεκτρονίων και εκπομπή ηλεκτρονίου Auger.

Κεφάλαιο 2

Η πρωτοβουλία της πειραματικής ομάδας του APAPES

2.1 Εισαγωγή

Η πρωτοβουλία APAPES - Atomic Physics with Accelerators: Projectile Electron Spectroscopy (http://apapes.physics.uoc.gr/) - Ατομική Φυσική με Επιταχυντές: Φασματοσκοπία ηλεκτρονίων Ιόντων Δέσμης, στον Επιταχυντή TANDEM του Ε.Κ.Ε.Φ.Ε "Δημόκριτος" ξεκίνησε το 2011 από τον Καθηγητή του Πανεπιστημίου Κρήτης κ. Θεόδωρο Τζούρο ο οποίος είχε την ιδέα της δημιουργίας μιας πειραματικής ομάδας ατομικής φυσικής, της πρώτης στην Ελλάδα, στο εργαστήριο του επιταχυντή TANDEM του Ε.Κ.Ε.Φ.Ε "Δημόκριτος", με αντικείμενο την φασματοσκοπία ηλεκτρονίων Auger 0 μοιρών και συγχρηματοδότηση από το πρόγραμμα ΘΑΛΗΣ[1]. Έτσι, η υλοποίηση αυτής της ιδέας ξεκίνησε στα τέλη του 2011 από μηδενική βάση με την προσθήκη της πειραματικής γραμμής $L45$ αποκλειστικά για φασματοσκοπία ηλεκτρονίων δέσμης ιόντων στο εργαστήριο TANDEM. Μετά από σκληρή δουλειά αλλά και πολλές γραφειοκρατικές καθυστερήσεις στο πρόγραμμα της χρηματοδότησης, τον Ιούλιο του 2014 έγιναν με επιτυχία οι πρώτες πειραματικές μετρήσεις και καταγράφηκε το πρώτο φάσμα Auger ηλεκτρονίων δέσμης ιόντων.

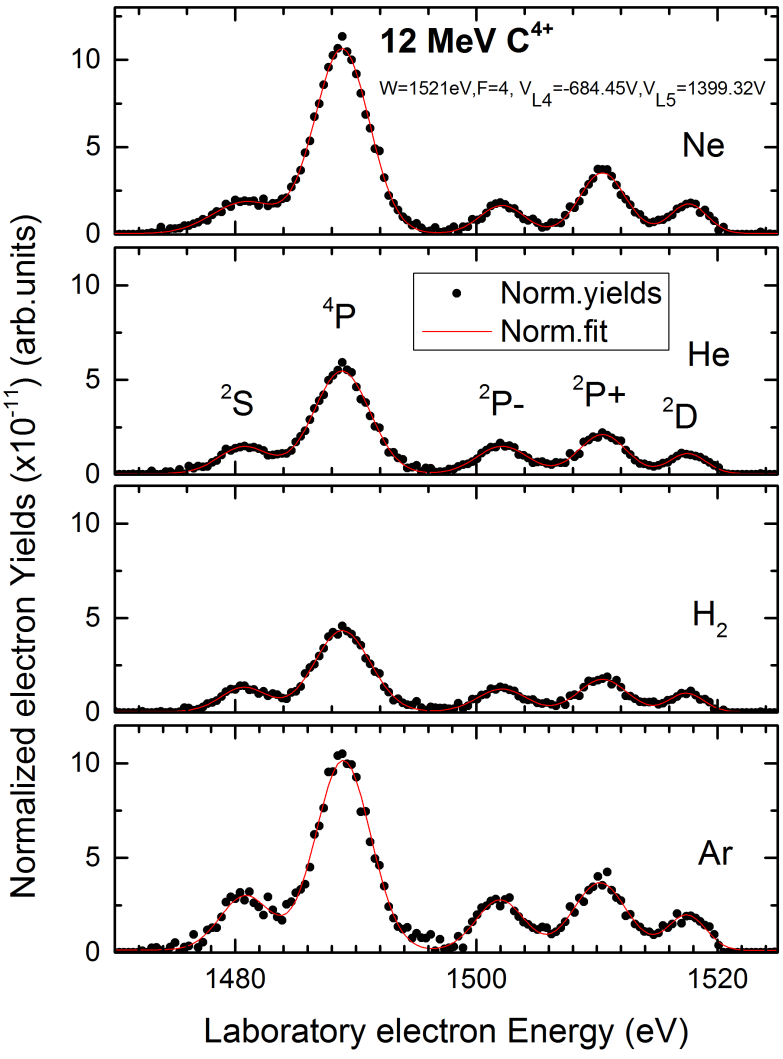
2.2 Φασματοσκοπία ηλεκτρονίων ιόντων δέσμης

Γενικά

Μια τυπική πειραματική διάταξη για φασματοσκοπία ηλεκτρονίων Auger 0^0 παρουσιάζεται στο σχ. 2.2. Η δέσμη ιόντων εισέρχεται στο διαφορικά αντλούμενο κελί που περικλείει τον αέριο-στόχο και συγκρούεται με αυτό. Στην περίπτωση μας, εντός του 50mm σε μήκος κελιού αναπτύσσονται πιέσεις 5-40 mTorr. Η πίεση μεταβάλλεται έτσι

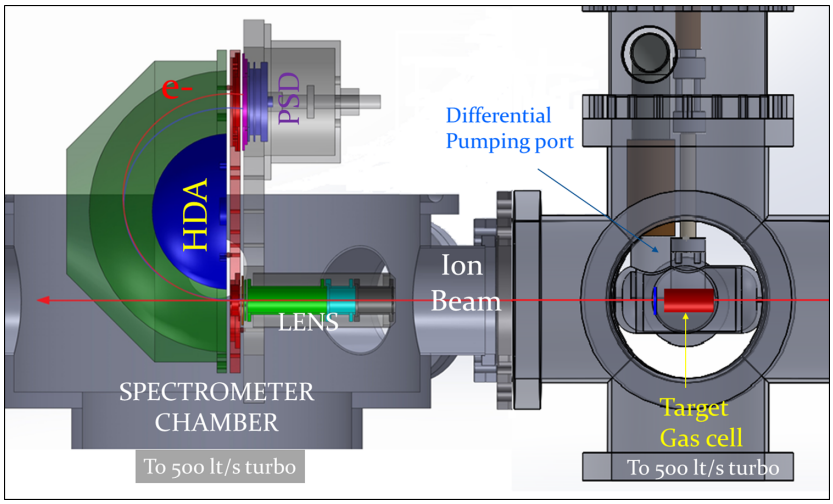
[1] Η ανακοίνωση για τις επιτυχείς προτάσεις έγινε από την ΓΓΕΤ στις 6/10/2011

ώστε να φροντίζουμε πάντοτε να έχουμε συνθήκες μίας και μόνο κρούσης. Η δέσμη ιόντων στην συνέχεια διέρχεται μέσα από το φασματόμετρο, εξέρχεται από το πίσω μέρος του και στην συνέχεια συλλέγεται στο τέλος σε ένα κλωβό Faraday (Faraday cup). Ένας αρκετά μεγάλος αριθμός ιόντων απαιτείται έτσι ώστε να ληφθεί ένα φάσμα καλής ποιότητας. Στην περίπτωση μας ένα καλό φάσμα όπως αυτά που παρουσιάζονται στο σχ. 2.1 μπορεί να ληφθεί σε μερικά μόλις λεπτά της ώρας.



Σχήμα 2.1: Τυπικά φάσματα άνθρακα φασματοσκοπίας ηλεκτρονίων ιόντων δέσμης σε κρούσεις 12 MeV C^{4+} με τα αέρια H_2, He, Ne και Ar.

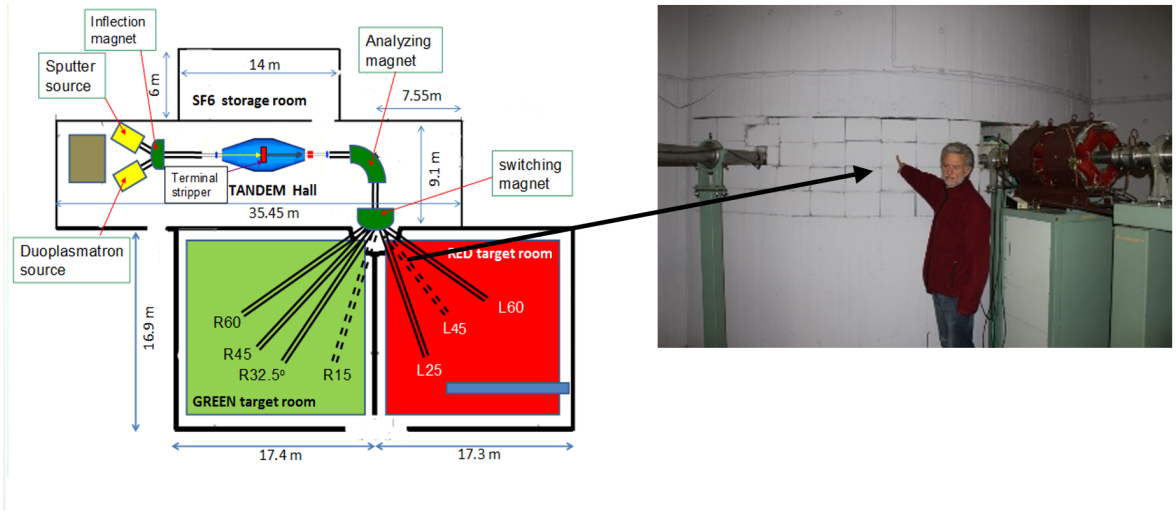
Τα ηλεκτρόνια Auger που εκπέμπονται ακαριαία μέσα από το κελί και αυτά που παράγονται κατά την πορεία της δέσμης προς τον αναλυτή από μετασταθείς καταστάσεις ή ακόμα και μέσα σε αυτόν, αναλύονται ενεργειακά με την βοήθεια ενός ημισφαιρικού αναλυτή οι ιδιότητες του οποίου περιγράφοντα παρακάτω. Τα ηλεκτρόνια μπορούν να επιβραδυνθούν πριν μπουν στον αναλυτή για την επίτευξη μεγαλύτερης διακριτικής ικανότητας στο φάσμα. Η διακριτική ικανότητα $R = \Delta E/E$ εξαρτάται από καθαρά γεωμετρικές παραμέτρους του αναλυτή που παραμένουν σταθερές, συνεπώς μειώνοντας την ενέργεια E μειώνεται αναγκαστικά και η ΔE. Ο παράγοντας επιβράδυνσης F ορίζεται ως $F = E/E_{pass}$, όπου E_{pass} είναι η ενέργεια των ηλεκτρονίων μετά από την επιβράδυνση που υφίστανται από την αρχική ενέργεια E [6].



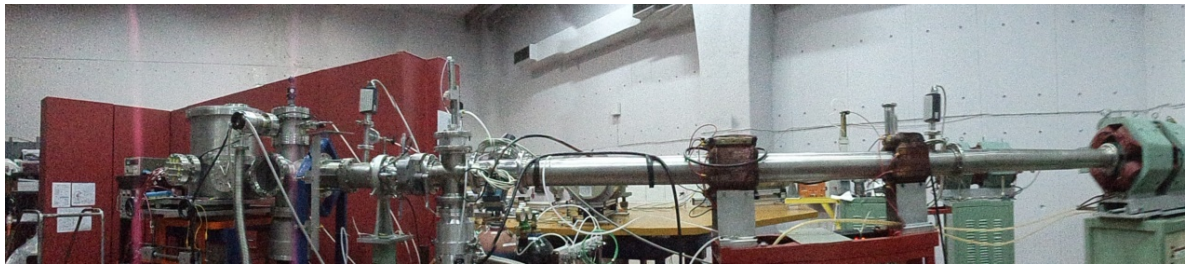
Σχήμα 2.2: Το σύστημα στόχου, αναλυτή, ανιχνευτή.

2.3 Τα κύρια μέρη της πειραματικής διάταξης του A-PAPES

Η πειραματική γραμμή του APAPES ξεκίνησε να κατασκευάζεται στα τέλη του 2011. Αποτελείται από α) τον ανοξείδωτο ατσάλινο σωλήνα μέσα στον οποίο κινείται η δέσμη ιόντων, β) δυο κατευθυντήρες δέσμης (steerrers) οι οποίοι δίνουν την δυνατότητα της αλλαγής της κατεύθυνσης της δέσμης, γ) δύο κλωβούς Faraday (Faraday Cups) τα οποία δίνουν την δυνατότητα της μέτρησης του ρεύματος της δέσμης ιόντων, δ) το κελί μέσα στο οποίο διοχετεύεται το αέριο-στόχος, ε) ένα σύστημα τροφοδοτικών τα οποία παρέχουν τις κατάλληλες τάσεις στον ημισφαιρικό αναλυτή, στον ηλεκτροστατικό φακό και σε άλλα σημεία του πειράματος, στ) τον ημισφαιρικό αναλυτή και τέλος ζ) το σύστημα του ανιχνευτή (position sensitive detector - PSD) μαζί με το σύστημα προ ενισχυτή και το σύστημα ψηφιοποίησης του σήματος, Data Acquisition system (DAQ). Στις εικόνες 2.3 και 2.4 φαίνονται τα αρχικά στάδια τοποθέτησης της νέας πειραματικής γραμμής $L45$ και ολοκληρωμένη η πειραματική γραμμή του APAPES.



Σχήμα 2.3: Η δημιουργία της πειραματικής γραμμής $L45$ του APAPES.



Σχήμα 2.4: Η πειραματική γραμμή $L45$ του APAPES.

2.4 Το κελί του αερίου στόχου

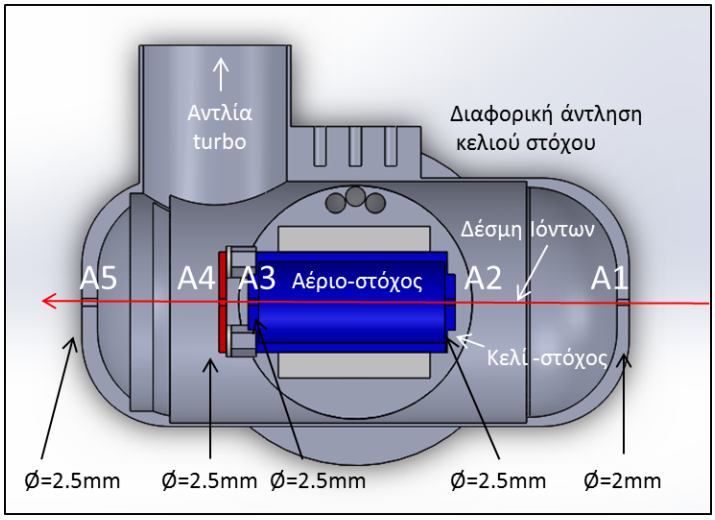
Το κελί του αέριου στόχου αποτελείται από δύο ομόκεντρους κυλίνδρους. Ο εσωτερικός κύλινδρος είναι 50 mm σε μήκος και έχει εξωτερική διάμετρο 25 mm, ενώ ο εξωτερικός κύλινδρος είναι 140 mm σε μήκος και έχει εξωτερική διάμετρο 63 mm. Οι δύο κύλινδροι είναι από ανοξείδωτο ατσάλι και είναι ηλεκτρικά απομονωμένοι μεταξύ τους. Κάθε ένας από τους κυλίνδρους έχει αποσπώμενες εισόδους - εξόδους των οποίων οι διάμετροι παρουσιάζονται στο πίνακα 2.1.

2.4.1 Η διαφορική άντληση του κενού

Η βασική ιδέα του διαφορικά αντλούμενου κελιού του αερίου στόχου αποτελείται από δύο ομόκεντρους κυλίνδρους. Έναν εσωτερικό και έναν εξωτερικό που τον περικλείει. Ο εξωτερικός κύλινδρος είναι συνδεδεμένος με μία μικρή στροβιλομοριακή αντλία κενού (80 l/s) η οποία αντλεί τον εσωτερικό του χώρο. Αυτό γίνεται για να αποφεύγεται η "ρύπανση" της πειραματικής γραμμής με το αέριο που χρησιμοποιείται ως στόχος με αποτέλεσμα να χαλάει το κενό στην πειραματική διάταξη. Όλο το σύστημα βρίσκεται

Πίνακας 2.1: Χαρακτηριστικά του κελιού αερίου-στόχου

Item		
Apertures (circular)	New Diameter (mm)	Old Diameter (mm)
A1 outer cell entrance	2.0	1.8
A2 inner cell entrance	2.5	1.7
A3 inner cell exit	2.5	1.8
A4 extra aperture	2.5	1.8
A5 outer cell exit	2.5	2.5
Inner cell length (outside dimension)	50.	
Outer cell length (outside dimension)	140	
Inner cell diameter (outside dimension)	25.	
Outer cell diameter (outside dimension)	63.	

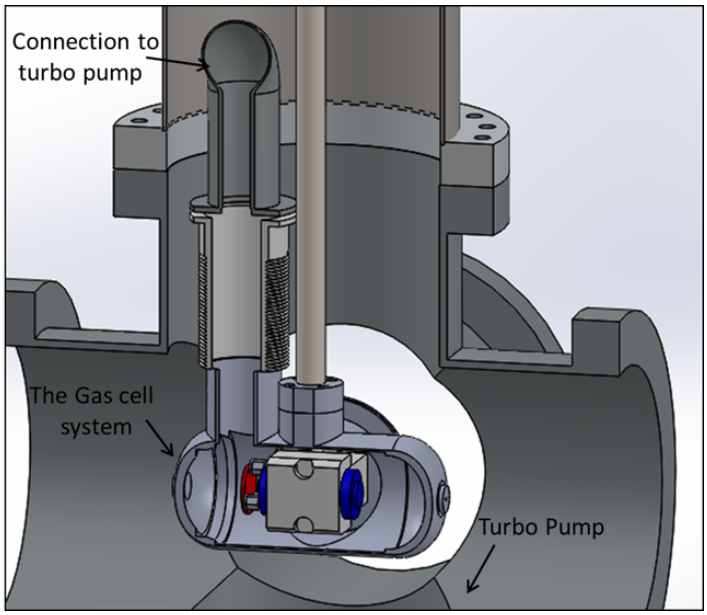


Σχήμα 2.5: Το διπλό κελί του αερίου-στόχου που χρησιμοποιείται στο πείραμα του APAPES για φασματοσκοπία ηλεκτρονίων Auger. Οι είσοδοι-έξοδοι της δέσμης ιόντων 1-5, έχουν διαμέτρους έως 2.5 mm έτσι ώστε να αποφεύγεται η διάχυση του αερίου έξω από το εξωτερικό κελί.

πάνω σε ένα 6-πλο σταυρό από ανοξείδωτο ατσάλι. Στην κάτω φλάντζα του σταυρού είναι τοποθετημένη ακόμα μια πολύ μεγαλύτερη στροβιλομοριακή αντλία (500 l/s) η οποία αντλεί τον χώρο για ακόμα καλύτερο κενό στην διάταξη σχ. 2.8.

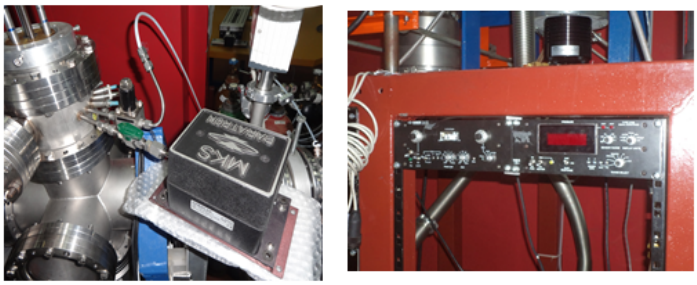
2.4.2 Η παροχή του κελιού με το αέριο- στόχο

Από ότι γνωρίζουμε και από προηγούμενα πειράματα τα φάσματα που προκύπτουν έχουν άμεση εξάρτηση από την πίεση του αερίου στόχου μέσα στο κελί. Πιο συγκεκρι-



Σχήμα 2.6: Ο μηχανισμός διαφορικής άντλησης αερίου.

μένα έχει παρατηρηθεί ότι υψηλή πίεση μέσα στο κελί δημιουργεί αυξημένο υπόστρωμα στο φάσμα. Αυτό το γεγονός καθιστά αναγκαίο ένα σύστημα που να διατηρεί και να σταθεροποιεί την πίεση σε συγκεκριμένες απόλυτες τιμές. Για να επιτευχθεί αυτό χρησιμοποιήθηκε ένας μετρητής απόλυτης πίεσης τύπου μανόμετρο πυκνωτή (capacitive manometer) της εταιρείας MKS Baratron και μία βαλβίδα ελέγχου ροής αερίου. Η αρχή λειτουργίας αυτού του συστήματος βασίζεται σε μια δυναμική ισορροπία ροής αερίου στο κελί - στόχο. Η πίεση του αερίου μετράται σε συγκεκριμένα χρονικά διαστήματα μεταφέροντας την πληροφορία στην μονάδα του Baratron η οποία συνδέεται με την μονάδα ελέγχου της παροχής του αερίου. Η μονάδα ελέγχου της βαλβίδας ανταποκρίνεται στην πληροφορία που λαμβάνει από την μονάδα του Baratron και αυξάνει ή μειώνει την ροή του αερίου έτσι ώστε αυτή να παραμένει σε ένα συγκεκριμένο επίπεδο. Όλο το σύστημα έχει παροχή από τέσσερα διαφορετικά αέρια (H_2, He, Ne, Ar) υψηλής καθαρότητας (99.999%) τα οποία μεταφέρονται μέσω ενός συστήματος πλαστικών σωλήνων.



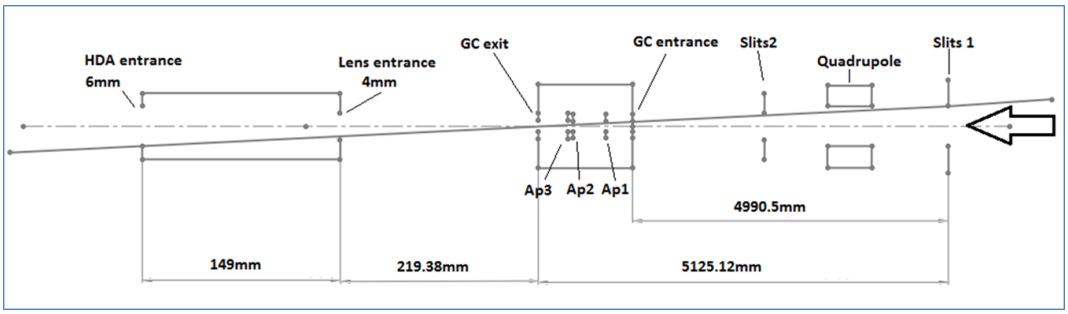
Σχήμα 2.7: Το σύστημα σταθεροποίησης πίεσης αερίου στόχου.

Σχήμα 2.8: Το σύστημα παροχής των αερίων στόχου.

2.4.3 Η ανάγκη κατασκευής μιας νέας βάσης ευθυγράμμισης

Μία από τις ιδιαιτερότητες της πειραματικής γραμμής του APAPES είναι ότι χρησιμοποιεί στόχο σε αέρια κατάσταση. Το γεγονός αυτό δυσκολεύει τις πειραματικές συνθήκες συγκριτικά με τις περιπτώσεις όπου χρησιμοποιείται στερεός στόχος. Αυτό συμβαίνει διότι το αέριο τείνει να διαχυθεί μέσα στην πειραματική γραμμή και να χαλάσει το απαραίτητο κενό για την διέλευση της δέσμης. Αυτό συμβαίνει επειδή τα ιόντα συγκρούονται με τα μόρια του αερίου έτσι ακριβώς όπως συμβαίνει και σε συνθήκες ατμοσφαιρικού αέρα.

Η ανάγκη για μια βάση ευθυγράμμισης μεγάλης ακρίβειας προκύπτει από το γεγονός ότι χρησιμοποιείται ένα σύστημα διαφορικά αντλούμενων κελιών τα οποία έχουν εισόδους-εξόδους διαμέτρων περίπου 2mm. Αυτό καθιστά αρκετά δύσκολη την διέλευση της δέσμης μέσα από το σύστημα των κελιών, και ακόμα πιο δύσκολη την διέλευση της χωρίς να προσπίπτει στα διαδοχικά τοιχώματα, γεγονός το οποίο πρέπει να αποφεύγεται μιας και δημιουργεί ηλεκτρόνια που μπορεί να συμβάλλουν στο υπόστρωμα στο πειραματικό φάσμα.



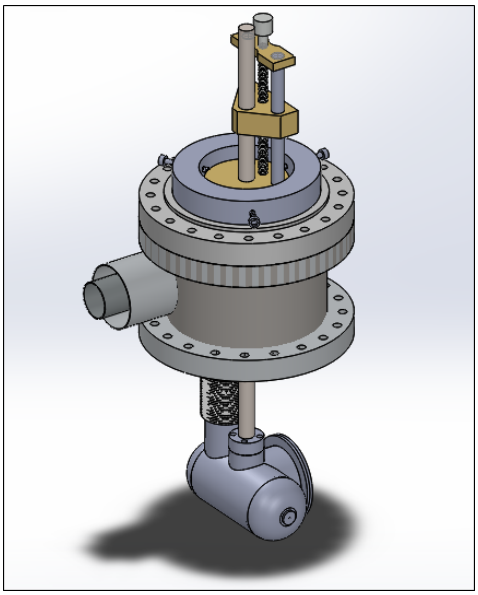
Σχήμα 2.9: Γεωμετρική μελέτη των συνθηκών ευθυγράμμισης του στόχου.

2.4.4 Η νέα βάση ευθυγράμμισης

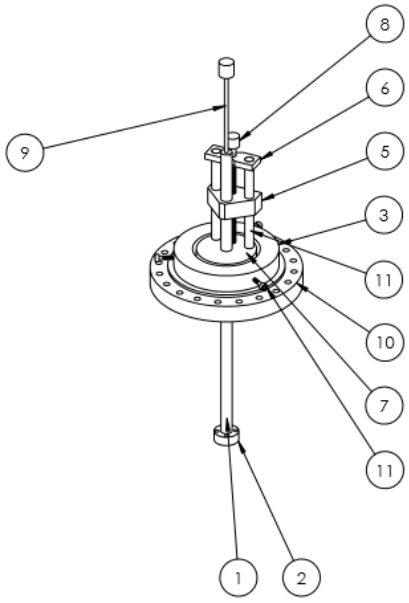
Η νέα βάση ευθυγράμμισης σχεδιάστηκε με την προοπτική να έχει την δυνατότητα να μετατοπίζει τον στόχο στο κατακόρυφο και στο οριζόντιο επίπεδο έτσι ώστε να μπορεί να ευθυγραμμιστεί πλήρως ο στόχος με την προσπίπτουσα δέσμη ιόντων. Στο σχ. 2.10 απεικονίζεται σε τρισδιάστατη μορφή το σύστημα βάσης ευθυγράμμισης, διαφορικής άντλησης κενού και στόχου. Ένα μέγεθος το οποίο μπορεί να μας δώσει μια εκτίμηση της χρησιμότητας της βάσης ευθυγράμμισης είναι το μετρούμενο ρεύμα ιόντων στο τελικό Faraday Cup. Χαρακτηριστικό είναι ότι ενώ με την προηγούμενη βάση ευθυγράμμισης καταφέρναμε να έχουμε ρεύμα της τάξεως των 2-3 nA στον στόχο, με την νέα βάση ευθυγράμμισης καταφέραμε να έχουμε ρεύμα μέχρι και 20 nA στον στόχο. Προς αυτήν την κατεύθυνση συνέβαλε επίσης η χρησιμοποίηση νέων εισόδων εξόδων του εξωτερικού και εσωτερικού κελιού με λίγο μεγαλύτερες διαμέτρους για την καλύτερη διέλευση της δέσμης. Στον πίνακα 2.1 παρουσιάζονται οι παλιές και οι νέες διάμετροι των εισόδων - εξόδων των κελιών.

2.5 Το φασματόμετρο ηλεκτρονίων

Το φασματόμετρο φαίνεται στο σχ. 2.13. Αποτελείται από διαφορετικά κομμάτια όπως ένας ημισφαιρικός αναλυτής (Hemispherical Deflector Analyzer, HDA), ένας ηλεκτροστατικός φακός τεσσάρων στοιχείων και ένας position sensitive detector (PSD) [7]. Ο αναλυτής αποτελείται από δύο ημισφαιρικά κελύφη με το εξωτερικό να έχει ακτίνα R_2 και το εσωτερικό R_1, 130.8mm και 72.4mm, αντίστοιχα. Τα δύο κελύφη του αναλυτή είναι ηλεκτρικά απομονωμένα μεταξύ τους και τίθενται σε δύο κατάλληλα δυναμικά $V1$ και $V2$ τέτοια ώστε τα ηλεκτρόνια που εισέρχονται στον αναλυτή να υφίστανται δύναμη απο το ηλεκτρικό πεδίο και να διαγράφουν καμπύλη τροχιά καταλήγοντας εστιασμένα ανάλογα την ενέργειά τους σε διαφορετικό σημείο πάνω στον ανιχνευτή θέσης. Ο φακός τεσσάρων στοιχείων εστιάζει τα ηλεκτρόνια της πηγής στην είσοδο του ημισφαιρικού αναλυτή, αυξάνοντας την συνολική στερεά γωνία αποδοχής ηλεκτρονίων του αναλυτή. Ο φακός μπορεί να χρησιμοποιηθεί για αύξηση της διακριτικής ικανότητας του φασματόμετρου, επιβραδύνοντας τα σωματίδια από μια αρχική ενέργεια T σε μια χαμηλότερη ενέργεια t ακριβώς πριν την είσοδο τους στον αναλυτή [8].



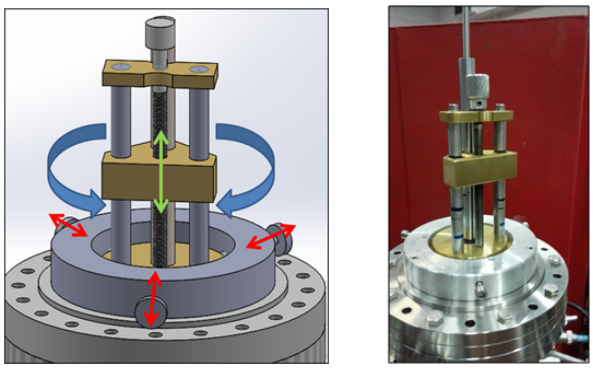
Σχήμα 2.10: Το σύστημα βάσης ευθυγράμμισης-στόχου.



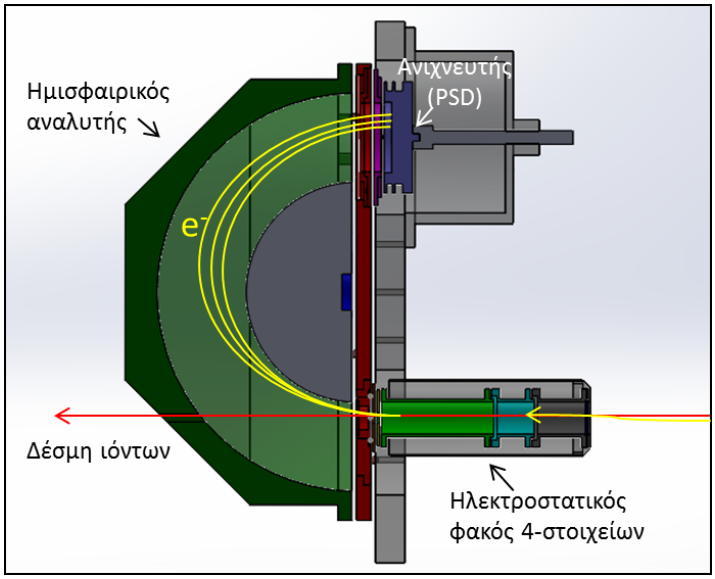
Σχήμα 2.11: Μηχανολογικό σχέδιο της νέας βάσης ευθυγράμμισης.

2.6 Ο ανιχνευτής

Ο ανιχνευτής που χρησιμοποιείται στην πειραματική διάταξη του APAPES είναι ένας δισδιάστατος ανιχνευτής θέσης (2-D Position Sensitive Detector, PSD), δηλαδή ένας



Σχήμα 2.12: Η νέα βάση ευθυγράμμισης του APAPES.



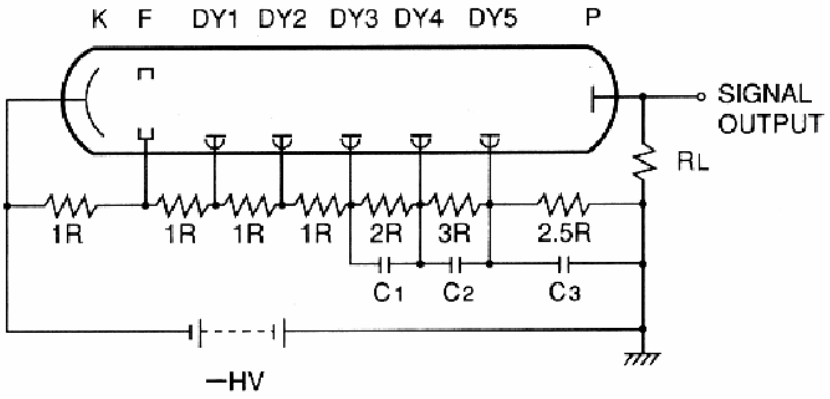
Σχήμα 2.13: Το φασματόμετρο αποτελούμενο από τον ημισφαιρικό αναλυτή και τον ηλεκτροστατικό φακό τεσσάρων στοιχείων.

ανιχνευτής με ευαισθησία ως προς την θέση του προσπίπτοντος σωματιδίου. Ο PSD αποτελείται από ένα σύστημα δυο πολυκαναλικών πλακών (Multi-Channel Plates, MCP) διαμέτρου 40mm οι οποίες δρουν ως ένα σύστημα ενίσχυσης του σήματος των προσπίπτοντων σωματιδίων με παρόμοια αρχή λειτουργίας με αυτή των δυνόδων. Ένας MCP είναι ένα σύστημα $\sim 10^4$ μικροδυνόδων, παράλληλες η μια στην άλλη [7].

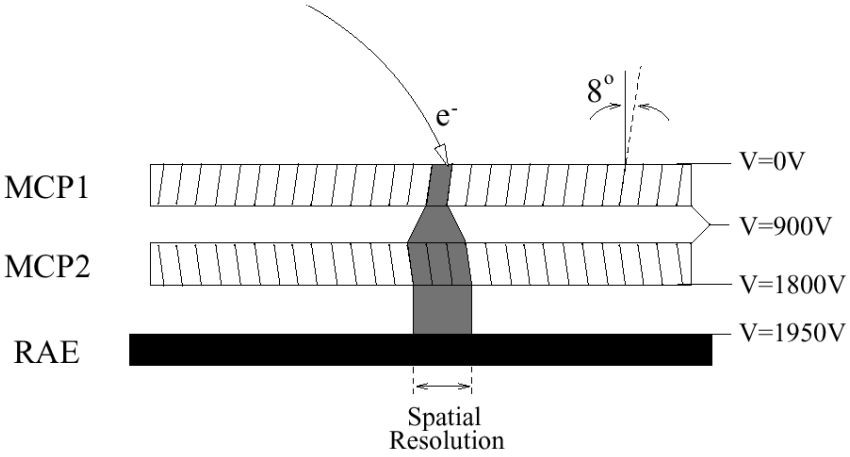
Μια σύντομη περιγραφή της λειτουργίας των δυνόδων συνοψίζεται ως εξής. Ένα ηλεκτρόνιο που παράγεται λόγω της κρούσης ενός σωματιδίου στον ανιχνευτή αρχικά επιταχύνεται προς την πρώτη δύνοδο στην οποία και προσπίπτει. Από την πρόσπτωση αυτή εξάγονται κατά μέσο όρο δ ηλεκτρόνια, όπου $\delta = kV$, όπου k σταθερά του υλικού και V η διαφορά δυναμικού μεταξύ των διαδοχικών δυνόδων. Τα ηλεκτρόνια αυτά επιταχύνονται προς την δεύτερη δύνοδο και εξάγονται κατά μέσο όρο δ^2 ηλεκτρόνια κ.ο.κ, δηλαδή δ^n για την n-οστή δύνοδο. Αυτή η διαδικασία συνεχίζεται μέχρις ότου τα

εξαγχθέντα ηλεκτρόνια να συλλεχθούν από την άνοδο και συμβάλλουν στην διαμόρφωση του τελικού σήματος (παλμού) εξόδου [9].

Ένα σύντομο σχέδιο της διάταξης των ηλεκτροδίων με την αλυσίδα αντιστάσεων για την διαίρεση της τάσης στις δυνόδους φαίνεται στο σχ. 2.14 ενώ μια σχηματική απεικόνιση της λειτουργίας των MCP φαίνεται στο σχ. 2.15.



Σχήμα 2.14: Ο μηχανισμός των δυνόδων.



Σχήμα 2.15: Ο πολυκαναλικός ανιχνευτής.

Κεφάλαιο 3

Απογύμνωση ιόντων

3.1 Εισαγωγή

Το πρόβλημα του υπολογισμού των φορτισμένων καταστάσεων που προκύπτουν από την κρούση δέσμης ιόντων με ένα υλικό απασχολεί από το 1954 [10], έως και στις μέρες μας [11]. Ακριβείς προβλέψεις πάνω στην διαμόρφωση των φορτισμένων καταστάσεων που προκύπτουν από την κρούση ιόντων με αέρια και στερεά μέσα ήταν απαραίτητες για τον σχεδιασμό νέων επιταχυντών και για την εκτίμηση των εξαγόμενων εντάσεων των διάφορων δεσμών φορτισμένων σωματιδίων [12].

Το φορτίο ενός ταχέως ιόντος που διέρχεται μέσα από κάποιο μέσο μεταβάλλεται, ως αποτέλεσμα δύο βασικών διαδικασιών ανταλλαγής φορτίου, της δέσμευσης (electron capture) ή της απώλειας (electron loss) ηλεκτρονίων. Στην δέσμευση ηλεκτρονίων η φορτισμένη κατάσταση q ενός ιόντος με ατομικό αριθμό Z μειώνεται κατά ένα όταν αποδέχεται ένα ηλεκτρόνιο από το στόχο - μέσο.

$$Z^q + e^- \longrightarrow Z^{(q-1)} \tag{3.1}$$

όπου $q \geq 0$.

Στην άλλη περίπτωση, η απώλεια ηλεκτρονίων είναι η διαδικασία με την οποία ένα ηλεκτρόνιο αποδεσμεύεται από ένα ιόν και το φορτίο του ιόντος αυξάνεται κατά ένα.

$$Z^q \longrightarrow Z^{(q+1)} + e^- \tag{3.2}$$

όπου $q \geq -1$.

Ύστερα από έναν ικανό αριθμό κρούσεων, μία κατάσταση ισορροπίας μεταξύ των διαδικασιών δέσμευσης και απώλειας ηλεκτρονίων επιτυγχάνεται, η οποία εξαρτάται μόνο από το είδος των ιόντων, την ταχύτητά τους, το στόχο και την κατάσταση στην οποία βρίσκεται αυτός (στερεή ή αέρια) [5].

3.2 Θεωρητικές μελέτες

Η πρώτη εκτενής θεωρητική μελέτη για την ανταλλαγή φορτίων παρουσιάστηκε από τον Bohr το 1948 [13]. Παρουσίασε αναλυτικές εκφράσεις για την δέσμευση η απώλεια ενός ηλεκτρονίου από ελαφριά και βαριά ιόντα διερχόμενα από ελαφριά και βαριά αέρια - στόχους. Ο Bell το 1953 [13] υπολόγισε αριθμητικά, ενεργές διατομές για δέσμευση και απώλεια ηλεκτρονίων από τυπικά προϊόντα σχάσης τα οποία απογυμνώνονταν σε βαρέα και ελαφριά αέρια σε χαμηλές πυκνότητες. Σε μία αναδιατύπωση της προσέγγισης του Bohr, οι Bohr και Lindhard (1954) [10] προσπάθησαν βασισμένοι σε κλασσικά και στατιστικά επιχειρήματα να δώσουν μια εκτενή ερμηνεία των μηχανισμών δέσμευσης και απώλειας ηλεκτρονίων από φορτισμένα βαρέα ιόντα. Ο Gluckstern το 1955 [14] προσάρμοσε τον τύπο του Bell έτσι ώστε να υπολογίσει ενεργές διατομές δέσμευσης και απώλειας ηλεκτρονίων από ιόντα μεσαίων ατομικών βαρών, $8 \leq Z \leq 18$, διερχόμενα μέσα από διάφορα αραιά αέρια [15].

Όλοι αυτοί οι συγγραφείς συνειδητοποίησαν την περιπλοκότητα των φαινομένων ανταλλαγής φορτίου, και η θεωρητική τους προσέγγιση βασίζεται σε λογικές, από φυσικής πλευράς, αλλά αυθαίρετες υποθέσεις. Είναι αναμενόμενο ως εκ τούτου, η εφαρμογή τέτοιων θεωριών να είναι περιορισμένη και, όπως έδειξαν και πειράματα, πολλά από τα προτεινόμενα μοντέλα χρειάζονται σημαντικές τροποποιήσεις. Για παράδειγμα, όλοι οι θεωρητικοί υπολογισμοί που αναπτύχθηκαν από τους παραπάνω περιορίζονται στην δέσμευση ή την απώλεια ενός και μόνο ηλεκτρονίου. Η πιθανότητα μεταφοράς πολλών ηλεκτρονίων σε μία κρούση θεωρήθηκε ότι είναι υπαρκτή αλλά γενικώς πολύ μικρή. Ωστόσο τα πειράματα έδειξαν ότι η απώλεια πολλών ηλεκτρονίων συμβαίνει με σχετικά υψηλή πιθανότητα. Συνήθως η ενεργός διατομή για την αποδέσμευση πολλών ηλεκτρονίων σε μία κρούση είναι μεγαλύτερη από αυτή της αποδέσμευσης μόνο ενός. Αυτό πρέπει να συνυπολογίζεται όταν γίνεται κάποια σύγκριση πειραματικών και θεωρητικών δεδομένων.

3.3 Ενεργές διατομές παραγωγής καταστάσεων φορτίου

Η ενεργός διατομή παραγωγής μιας κατάστασης φορτίου μέσω δέσμευσης ή απώλειας ηλεκτρονίων όταν ταχέα ιόντα συγκρούονται με άτομα ή μόρια στόχου, παρέχει την θεμελιώδη πληροφορία για την ακριβή περιγραφή των καταστάσεων φορτίου που παράγονται σε τέτοιου είδους κρούσεις. Ένα πλήθος ερευνητών αφιέρωσαν σημαντική προσπάθεια για τον υπολογισμό και την μέτρηση αυτών των ενεργών διατομών. Παρόλα αυτά, ενώ παρατηρείται μια λογική συμφωνία μεταξύ θεωρίας και πειράματος στις πιο απλές περιπτώσεις, όπως όταν πρωτόνια κινούνται μέσα από υδρογόνο, στην περίπτωση βαρέων ιόντων οι διαδικασίες που συμμετέχουν στην δέσμευση ή απώλεια ηλεκτρονίων είναι γενικώς τόσο περίπλοκες που δεν μπορούν να έχουν μια ακριβή και εμπεριστατωμένη περιγραφή. Το μεγαλύτερο μέρος των θεωρητικών μελετών βασίζεται σε απλοποιημένα μοντέλα και γενικώς αυθαίρετα συμπεράσματα. Ως εκ τούτου, δεν προκαλεί έκπληξη το

ότι αυτά τα μοντέλα μπορούν να εξάγουν μόνο προσεγγιστικά αποτελέσματα τα οποία υπόκεινται σε περιορισμούς όσον αφορά τις παραμέτρους Z, v, q και Z_r [15].

3.4 Ημι-εμπειρικές μέθοδοι προσδιορισμού καταστάσεων στην απογύμνωση ιόντων

Η θεωρητική πρόβλεψη των φορτισμένων καταστάσεων που προκύπτουν, επιτυγχάνεται σε κάποιο βαθμό μέσω ημι-εμπειρικών μαθηματικών σχέσεων οι οποίες εξάγονται μέσω προσεγγίσεων των πειραματικών δεδομένων. Η χρησιμότητα που έχουν αυτοί οι τύποι στον χειρισμό των επιταχυντών Tandem Van de Graaff είναι θεμελιώδης. Εκτός αυτού όμως, είναι επίσης απαραίτητοι για πειραματικές ομάδες ατομικής φυσικής όπως αυτής του APAPES στην λήψη πειραματικών δεδομένων. Καταρχάς το φάσμα ηλεκτρονίων Auger δέσμης παρουσιάζει σημαντικές διαφορές αναλόγως με το αν η δέσμη ιόντων έχει παραχθεί με χρήση στερεού μέσου (φύλλου άνθρακα) ή με χρήση αέριου μέσου (N_2) [16]. Το συγκεκριμένο φαινόμενο περιγράφεται αναλυτικά παρακάτω. Κατά δεύτερον η ενεργός διατομή παραγωγής μιας φορτισμένης κατάστασης εξαρτάται σε μεγάλο βαθμό από την ενέργεια που έχει η δέσμη κατά την κρούση της με το μέσο που χρησιμοποιείται για την απογύμνωση. Ως εκ τούτου, για την παραγωγή συγκεκριμένων φορτισμένων καταστάσεων απαιτείται η χρήση ενός μετα-απογυμνωτή (post stripper - PS) σε σημείο μετά από τον απογυμνωτή του τερματικού του επιταχυντή, όπου τα σωματίδια της δέσμης ιόντων έχουν επιταχυνθεί σε πολύ μεγαλύτερες ενέργειες. Κατά τις δεκαετίες διερεύνησης του συγκεκριμένου αντικειμένου έχουν διαμορφωθεί αρκετοί ημι-εμπειρικοί τύποι για την πρόβλεψη της πιθανότητας δημιουργίας των διαφόρων φορτισμένων καταστάσεων. Μερικοί από τους πιο δημοφιλής περιγράφονται στην συνέχεια.

Σύμφωνα με την ημι-εμπειρική σχέση του R. O. Sayer [12] η οποία έχει προκύψει από προσομοίωση πειραματικών δεδομένων, η κατανομή των πιθανοτήτων των φορτισμένων καταστάσεων μπορεί να περιγραφεί από την ασύμμετρη εξίσωση:

$$F_q = F_m \exp(\frac{-0.5\, t^2}{1 + \epsilon\, t}) \tag{3.3}$$

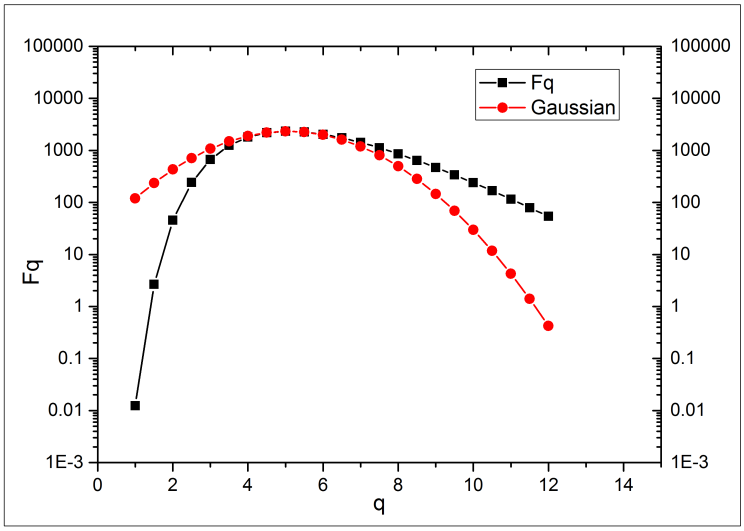
όπου

$$t = \frac{q - q_0}{\rho} \tag{3.4}$$

και F_q η κατανομή των φορτισμένων καταστάσεων, q_0 η κατάσταση φορτίου με την μεγαλύτερη ένταση. Όταν ο παράγοντας ασυμμετρίας $\epsilon \to 0$, η κατανομή της συνάρτησης τείνει στην Γκαουσσιανή εύρους ρ, $q \to q_0$ και $\rho\, F_m \to 1/\sqrt{2\pi}$.

Οι V.S. Nikolaev και I.S. Dmitriev [17] ανέπτυξαν έναν άλλον ημι-εμπειρικό τύπο για τον προσδιορισμό της μέσης τιμής φορτίου i με ένα εύρος d της ισορροπημένης κατανομής φορτισμένων καταστάσεων από πειραματικά δεδομένα για $Z \geq 20$:

$$\frac{i}{Z} = [1 + (\frac{v}{Z^{\alpha} v'})^{-\frac{1}{k}}]^{-k} \tag{3.5}$$



Σχήμα 3.1: Διάγραμμα πιθανοτήτων παραγωγής καταστάσεων φορτίου συναρτήσει της τιμής του φορτίου σύμφωνα με τον ημι-εμπειρικό τύπου του R. O. Sayer για $F_m = 23.3$, $q_0 = 5.07$, $\rho = 1.67$, $\epsilon = 0.31$. Η κόκκινη γραμμή αντιστοιχεί σε $\epsilon = 0$, δηλ. Γκαουσιανή κατανομή.

όπου $\alpha = 0.45$, $k = 0.6$, $v' = 3.6 \times 10^8$ cm/sec.

Τέτοιοι τύποι, όπως αυτός του H.D. Betz [15] που παρουσιάζεται από κάτω υπολογίζουν θεωρητικά την διακύμανση των φορτισμένων καταστάσεων.

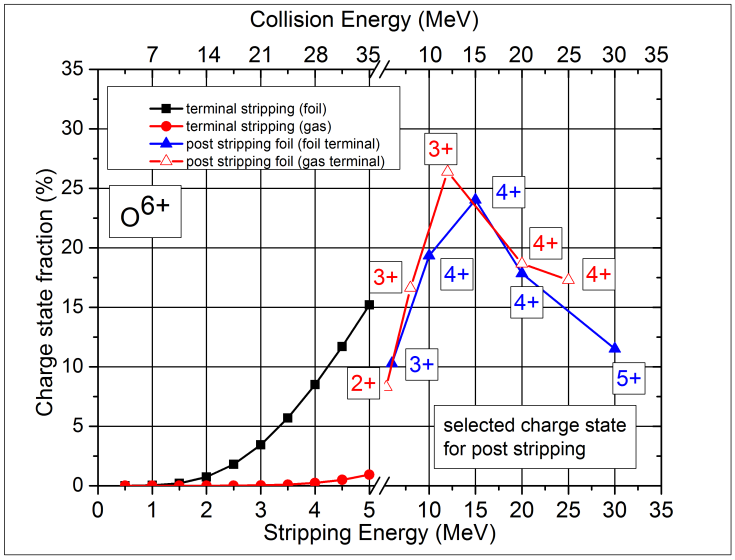
$$\frac{dY_q(x)}{dx} = \sum_{q' \neq q} q'[\sigma(q', q)Y'_q(x) - \sigma(q, q')Y_q(x)] \tag{3.6}$$

Όπου το Y_q υποδηλώνει το κομμάτι των ιόντων που έχουν φορτίο q (με την κανονικοποίηση $\sum_q Y_q(x) = 1$), και το x, αναλόγως από τις μονάδες που επιλέγονται για το σ, είναι ο αριθμός των ατόμων/cm^2 ή των μορίων/cm^2 στην πορεία των ιόντων.

Το φορτίο της κατάστασης που προκύπτει εξαρτάται από παράγοντες όπως ο ατομικός αριθμός των ιόντων της δέσμης, καθώς και από την ταχύτητα της δέσμης. Αρχικά είχε επικρατήσει η άποψη ότι με τους παραπάνω παράγοντες συγκεκριμένους κάθε φορτισμένη κατάσταση αποκτά μια ισορροπημένη πιθανότητα να δημιουργηθεί, η οποία είναι ανεξάρτητη από την πυκνότητα του στόχου ή από την αρχική κατάσταση φορτίου του προσπίπτοντος ιόντος [15]. Σύγχρονες ερευνητικές ομάδες όμως έδειξαν ότι αυτό δεν ισχύει και επικεντρώνουν την έρευνα τους στην εξάρτηση της κατανομής των δημιουργούμενων φορτισμένων καταστάσεων από το αρχικό φορτίο των ιόντων που υφίσταται την απογύμνωση όπως και από την πυκνότητα του στόχου [11]. Οι έρευνες αυτές δείχνουν ότι στην περίπτωση της απογύμνωσης με φύλλα άνθρακα, η πυκνότητα παίζει σημαντικό ρόλο στην τελική κατανομή των φορτισμένων καταστάσεων.

3.5 Η ανάγκη για έναν μετα-απογυμνωτή ηλεκτρονίων

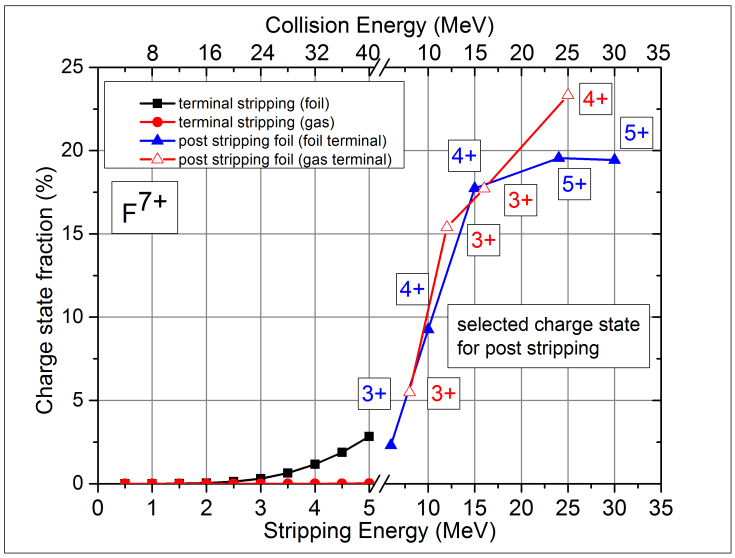
Γνωρίζοντας ότι το δυναμικό στο τερματικό του επιταχυντή TANDEM μπορεί να φτάσει μια μέγιστη τιμή 5 MV και ότι η δέσμη ιόντων που παράγεται στην πηγή μπορεί να έχει αποκλειστικά φορτίο $Q = -1$, θέτει τον περιορισμό ότι η ενέργεια απογύμνωσης στο τερματικό του επιταχυντή μπορεί να γίνει για ενέργειες δέσμης 0-5 MeV. Ημι-εμπειρικοί τύποι που έχουν αναπτυχθεί [4, 3], δείχνουν ότι συγκεκριμένες υψηλά φορτισμένες καταστάσεις δεν μπορούν να επιτευχθούν μέσω κρούσεων για αυτό το εύρος ενεργειών. Αντιθέτως, πολύ υψηλότερη ενέργεια κρούσης απαιτείται για την επίτευξη τέτοιων καταστάσεων. Για αυτόν τον λόγο είναι απαραίτητο ένα δεύτερο σημείο απογύμνωσης της δέσμης σε σημείο μετά τον αναλυτή μαγνήτη, όπου η κατάλληλα φορτισμένη στάθμη της δέσμης επιλέγεται για περαιτέρω απογύμνωση [18]. Αυτό επετεύχθη με την κατασκευή ενός συστήματος μετα-απογυμνωτών (post stripper - PS) ηλεκτρονίων.



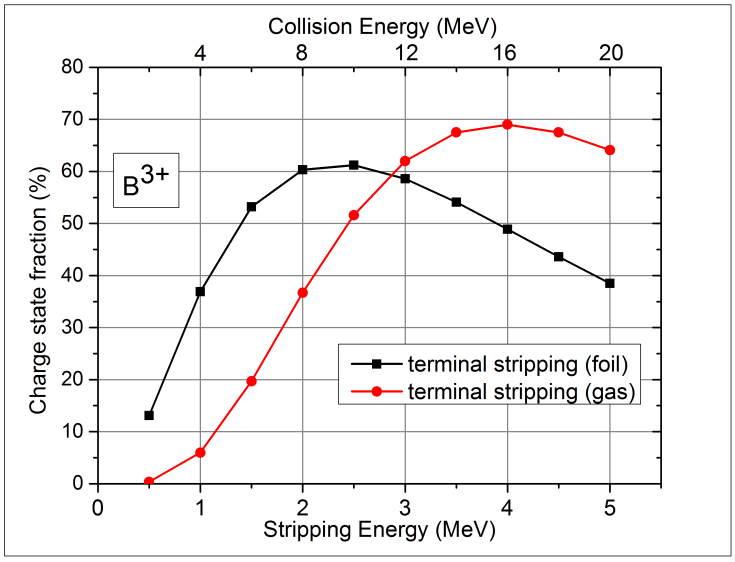
Σχήμα 3.2: Διάγραμμα πιθανότητας παραγωγής της φορτισμένης στάθμης O^{6+} συναρτήσει της ενέργειας κρούσης είτε στο τερματικό του επιταχυντή (terminal stripping), είτε σε μετέπειτα σημείο (post-stripping) με χρήση φύλλου άνθρακα ή αερίου N_2.

3.6 Ο απογυμνωτής ηλεκτρονίων φύλλων άνθρακα ιόντων δέσμης.

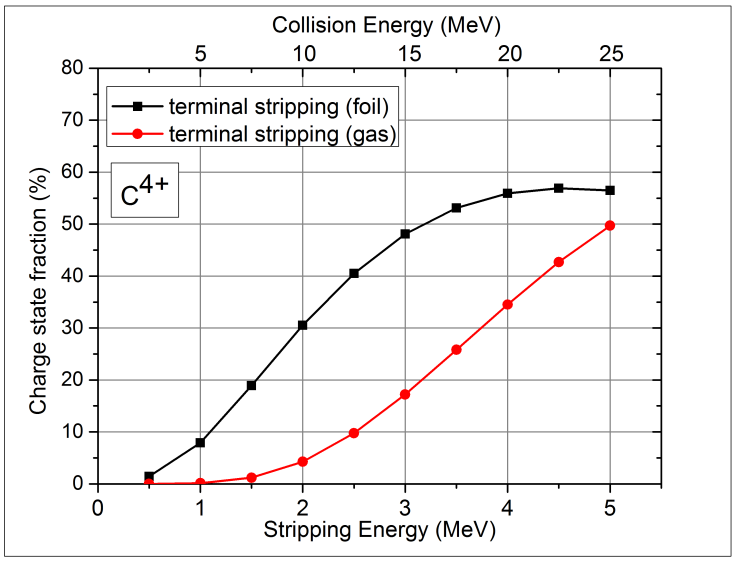
3.7 Ο απογυμνωτής ηλεκτρονίων αερίου ιόντων δέσμης.



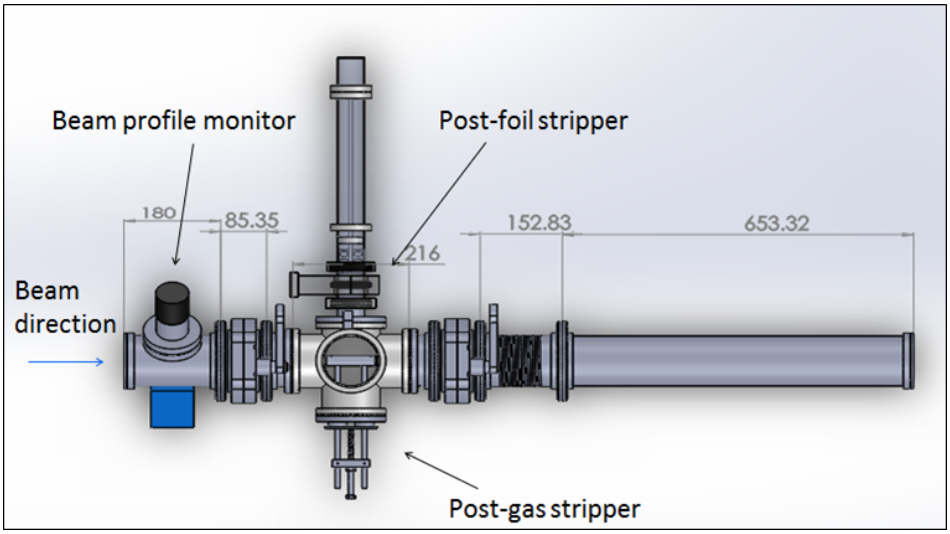
Σχήμα 3.3: Διάγραμμα πιθανότητας παραγωγής της φορτισμένης στάθμης F^{7+} συναρτήσει της ενέργειας κρούσης είτε στο τερματικό του επιταχυντή (terminal stripping), είτε σε μετέπειτα σημείο (post-stripping) με χρήση φύλλου άνθρακα ή αερίου N_2.



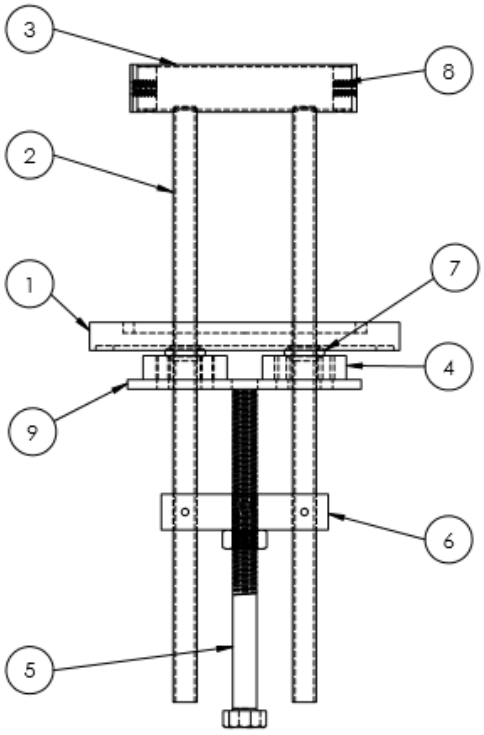
Σχήμα 3.4: Διάγραμμα πιθανότητας παραγωγής της φορτισμένης στάθμης B^{3+} συναρτήσει της ενέργειας κρούσης στο τερματικό του επιταχυντή (terminal stripping), καθώς και η ενέργεια που αποκτά τελικά η δέσμη ιόντων.



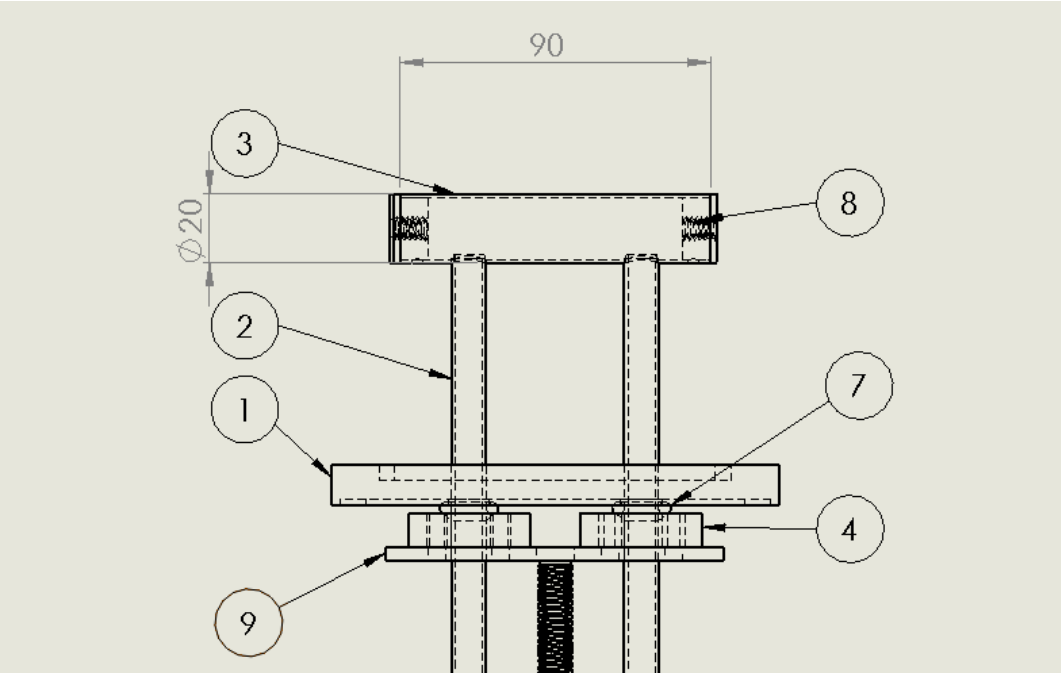
Σχήμα 3.5: Διάγραμμα πιθανότητας παραγωγής της φορτισμένης στάθμης C^{4+} συναρτήσει της ενέργειας κρούσης (Collision Energy) στο τερματικό του επιταχυντή (terminal stripping), καθώς και η ενέργεια που αποκτά τελικά (Stripping Energy) η δέσμη ιόντων μετά την τελική απογύμνωση (post-stripping).



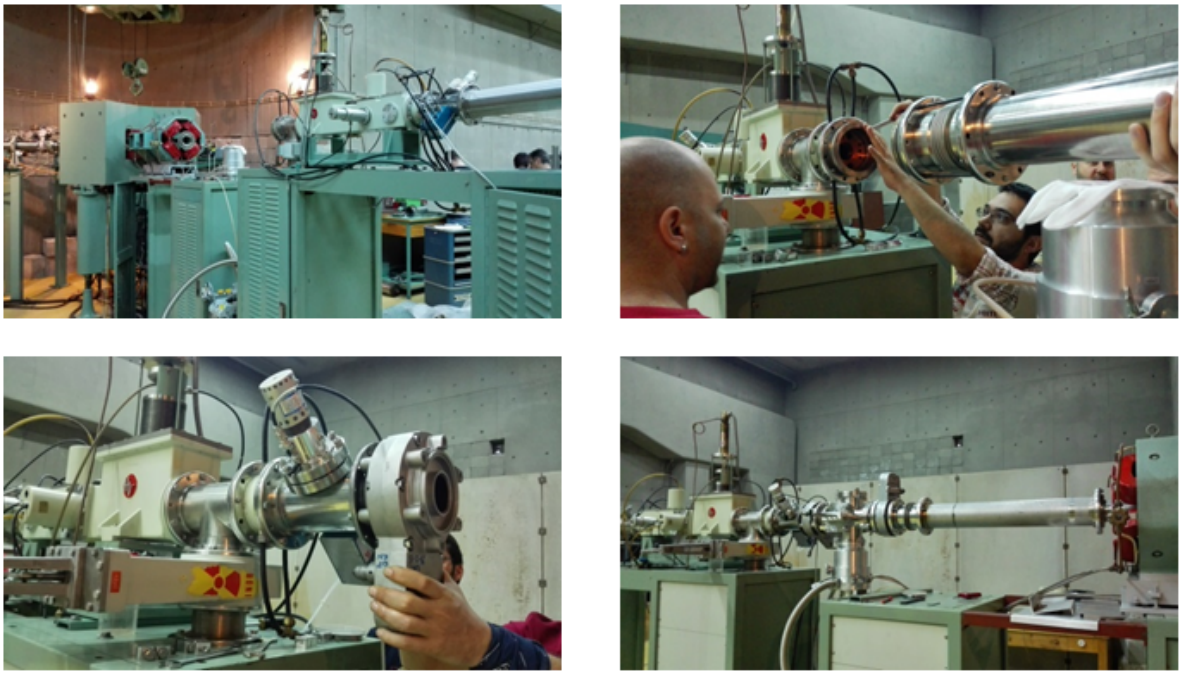
Σχήμα 3.6: Το σύστημα των απογυμνωτών ηλεκτρονίων.



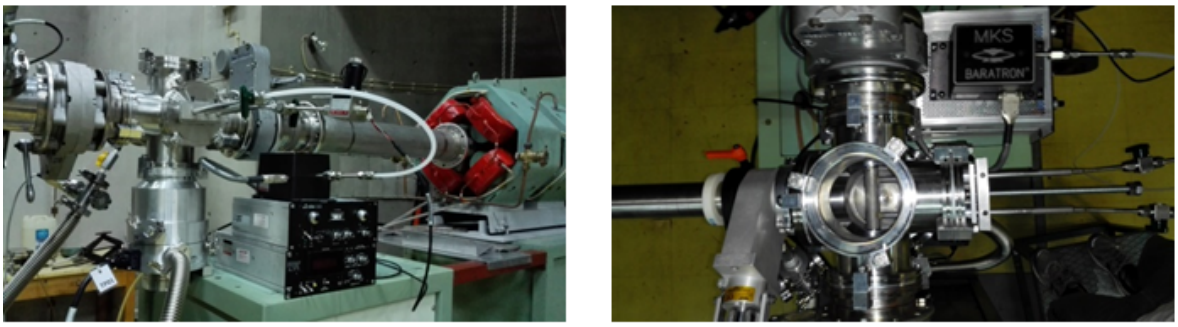
Σχήμα 3.7: Μηχανολογικό σχέδιο του αερίου απογυμνωτή ηλεκτρονίων.



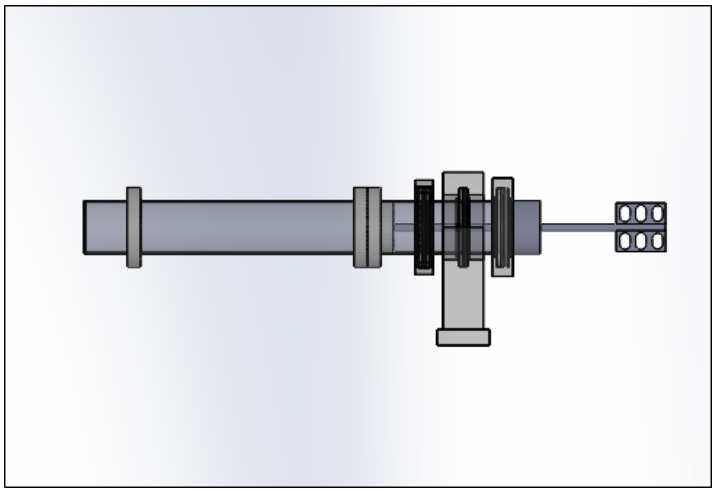
Σχήμα 3.8: Κοντινή εικόνα του μηχανολογικού σχεδίου του αέριου απογυμνωτή ηλεκτρονίων.



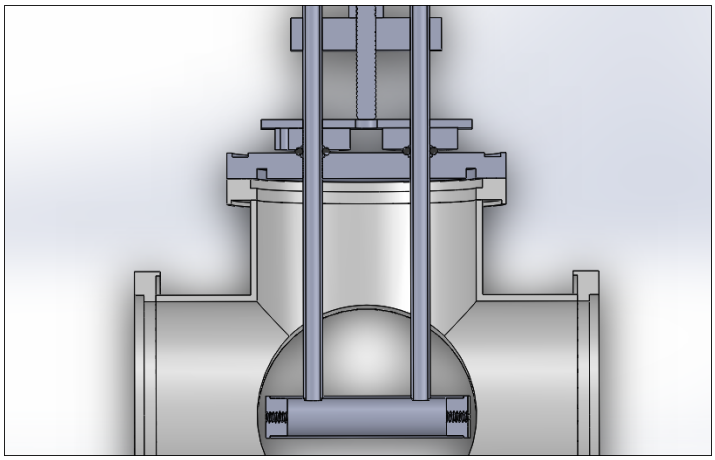
Σχήμα 3.9: Εργασίες εγκατάστασης των απογυμνωτών ηλεκτρονίων.



Σχήμα 3.10: Η ολοκληρωμένη εγκατάσταση των απογυμνωτών ηλεκτρονίων.



Σχήμα 3.11: Ο απογυμνωτής ηλεκτρονίων ιόντων δέσμης φύλλων άνθρακα.



Σχήμα 3.12: Ο απογυμνωτής ηλεκτρονίων αερίου ιόντων δέσμης.

Κεφάλαιο 4

Φασματοσκοπία ηλεκτρονίων Auger ιόντων δέσμης ηλιοειδών ατόμων

4.1 Φάσμα ηλεκτρονίων Auger C^{4+} + Ne

4.2 Παραγωγή της κατάστασης C^{4+} με χρήση απογυμνωτή ηλεκτρονίων φύλλου άνθρακα και αερίου N_2

Energy MeV	Terminal MV	Analyzed q	Terminal stripper	Post stripper	Final C^{4+} fraction
6	1.50	3	Foil	Gas	33.0%
	1.50	3	Foil	Foil	29.5%
	2.00	2	Gas	Foil	23.9%
9	2.25	3	Foil	Gas	30.0%
	2.25	3	Gas	Gas	31.9%
	2.25	3	Foil	Gas	30.0%
	2.25	3	Foil	Foil	18.5%
12	2.40	4	Foil	-	39%
	3.00	3	Foil	-	39%
	3.00	3	Gas	Gas	26%
	3.00	3	Foil	Gas	16%
18	3.60	4	Foil	-	54%
	3.60	4	Gas	-	27.5%
	4.50	3	Gas	Gas	7.2%

Σχήμα 4.1: Υπολογισμός των πιθανοτήτων παραγωγής της κατάστασης C^{4+} με χρήση απογυμνωτή ηλεκτρονίων φύλλου άνθρακα και αερίου. Αποτελέσματα από το πρόγραμμα TARDIS [19].

Ευχαριστίες

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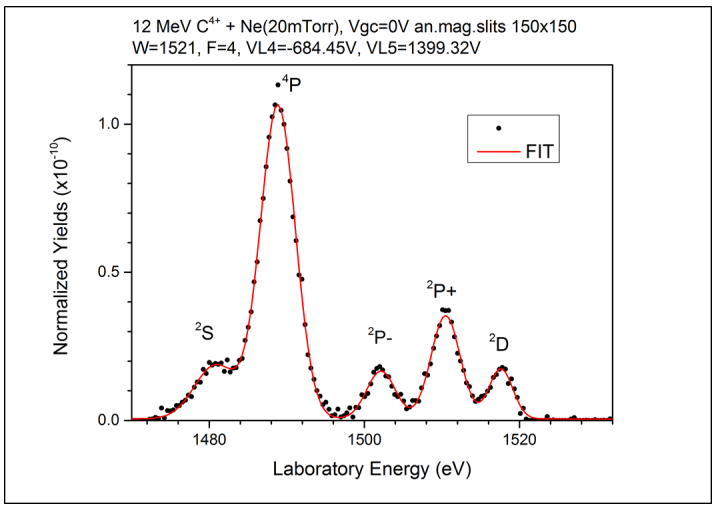
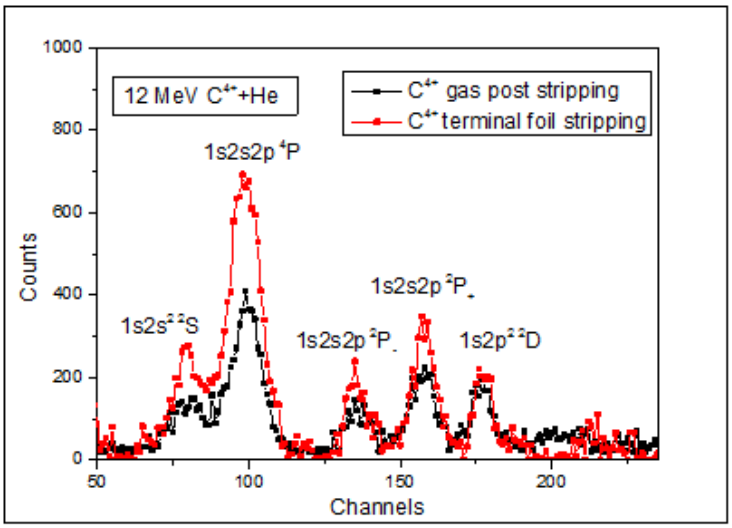


Σχήμα 4.2: Φάσμα ηλεκτρονίων Auger 12 MeV C^{4+} + Ne. Η δημιουργία της κατάστασης C^{4+} έγινε με χρήση απογυμνωτή φύλλων άνθρακα (carbon foils) στο τερματικό του επιταχυντή.



Σχήμα 4.3: Φάσμα ηλεκτρονίων Auger 12 MeV C^{4+} + He. Η δημιουργία της κατάστασης C^{4+} έγινε με χρήση απογυμνωτή φύλλων άνθρακα (carbon foils) στο τερματικό του επιταχυντή (κόκκινη γραμμή) και με απογυμνωτή αερίου N_2 στον post-stripper (μαύρη γραμμή).

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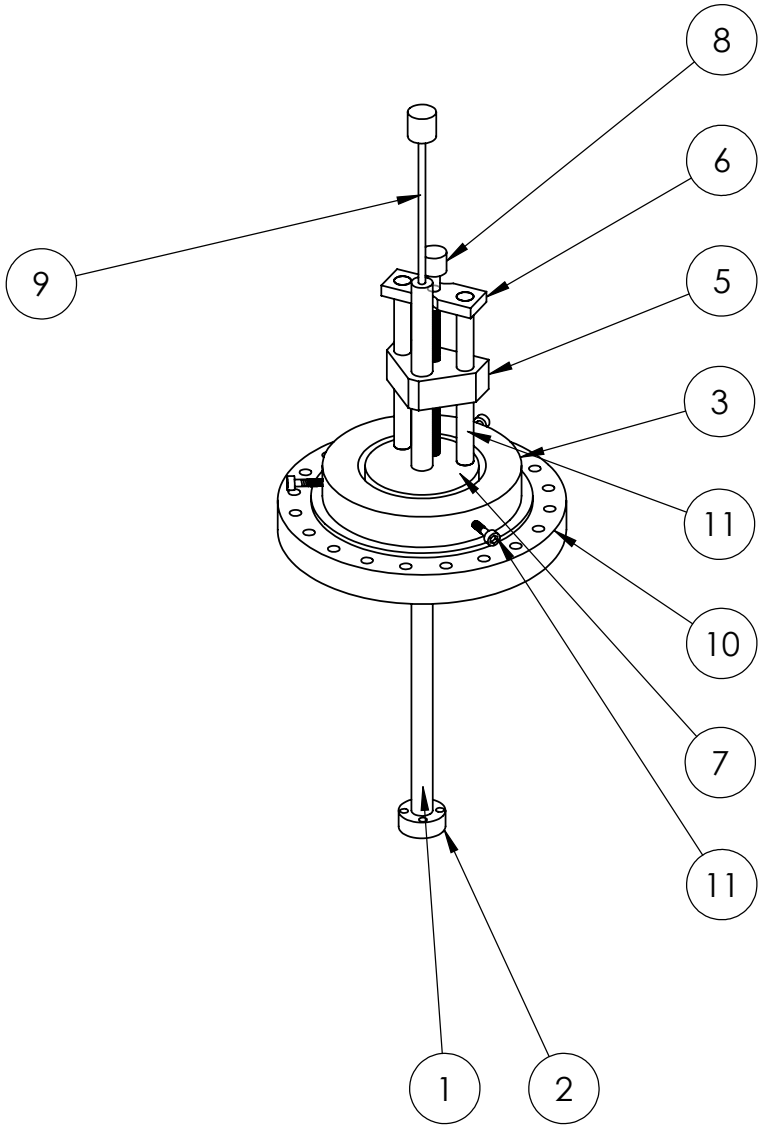
Παράρτημα Α΄

Μηχανολογικά σχέδια



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:	DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING / REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

APAPES GAS CELL TRANSLATION STAGE

MATERIAL:

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A4

WEIGHT:

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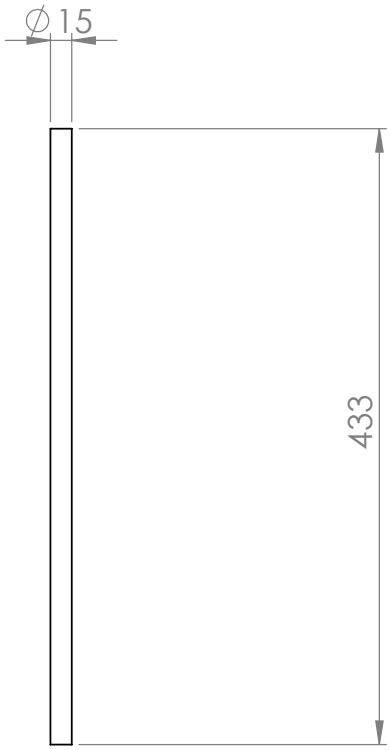
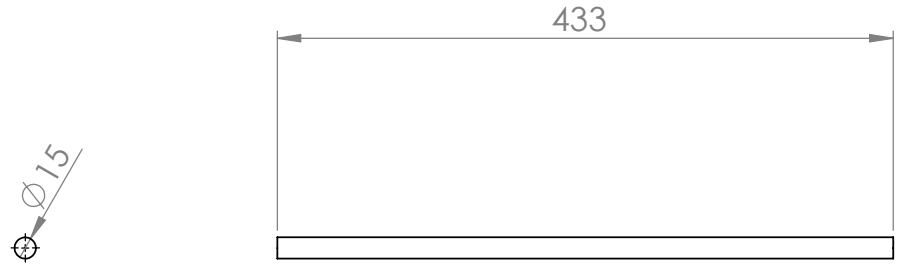
SHEET 1 OF 12





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PART 1 (ROD)

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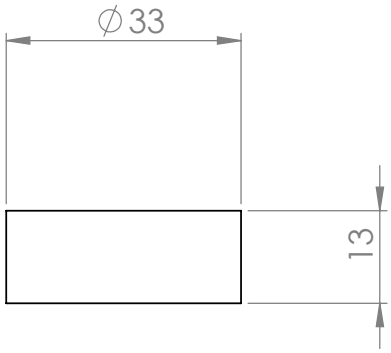
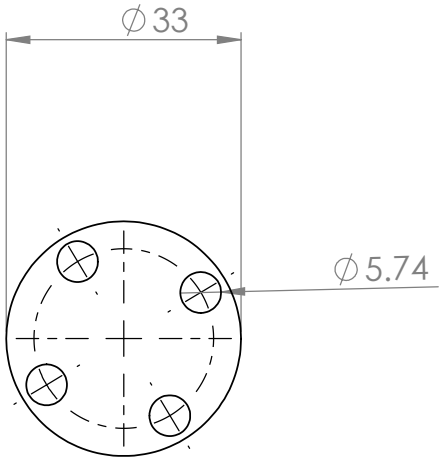
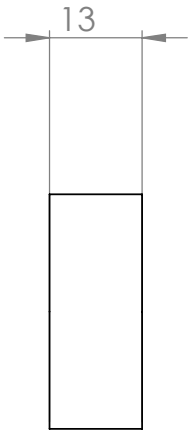
SHEET 2 OF 12







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CHK'D			
APPV'D			
MFG			
Q.A			

TITLE: PART 2 (CONNECTION WITH GAS CELL)

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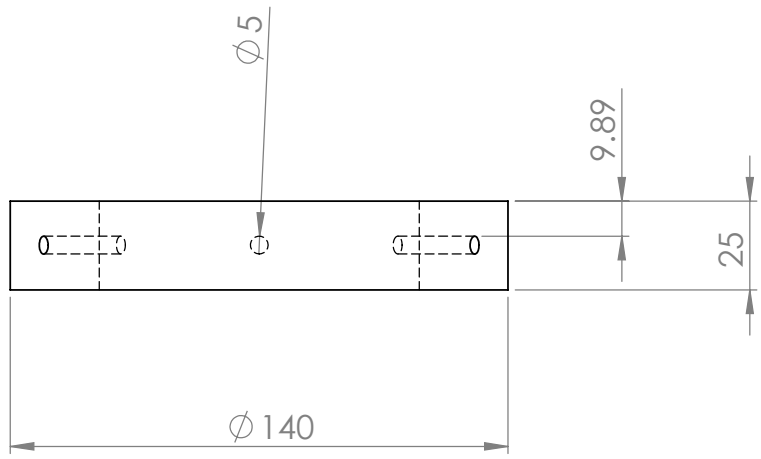
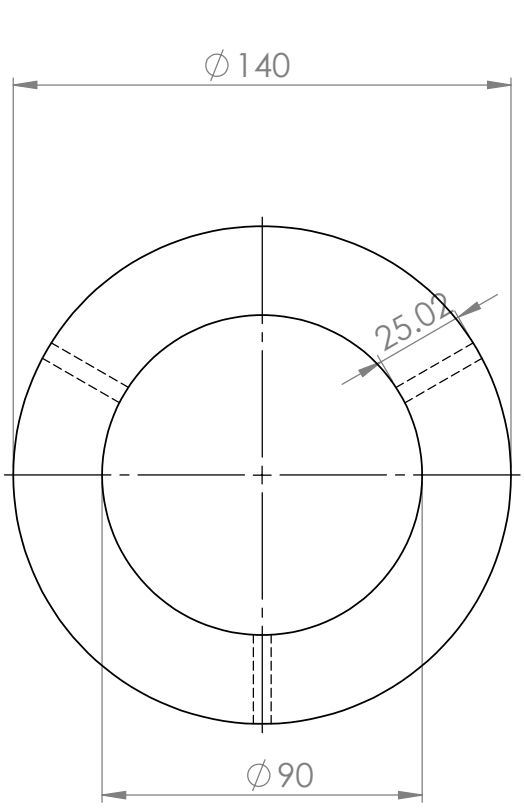
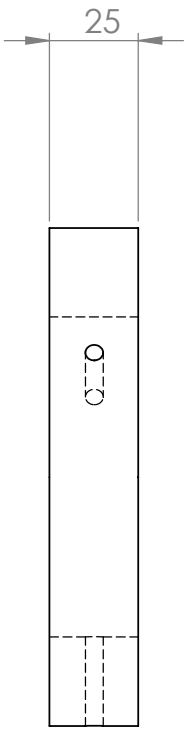
SHEET 3 OF 12







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APPV'D			
MFG			
Q.A			

PART 3

MATERIAL:

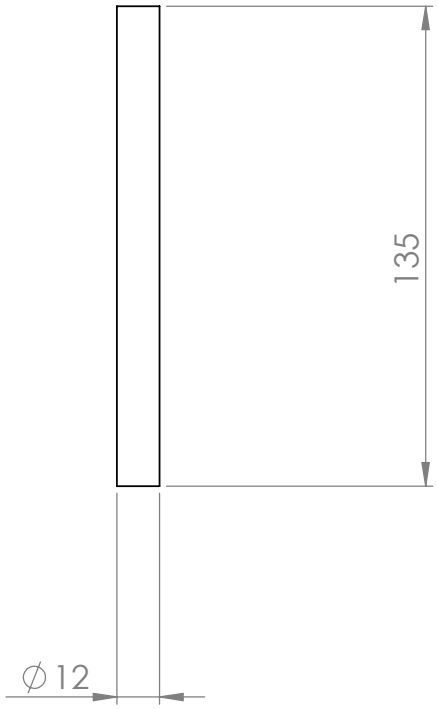
DWG NO. Assem131215

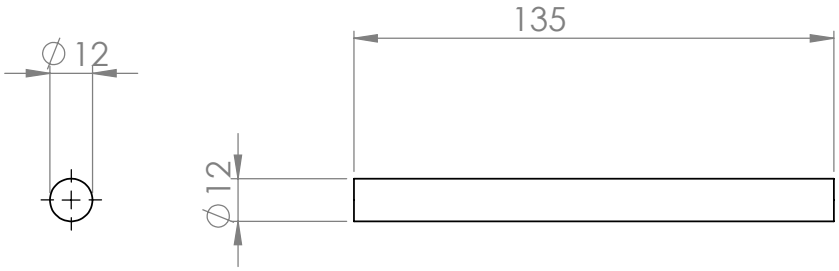
A4

WEIGHT:

SCALE:1:10

SHEET 4 OF 12





UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:	DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING / REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

PART 4 (ROD) X2

MATERIAL:

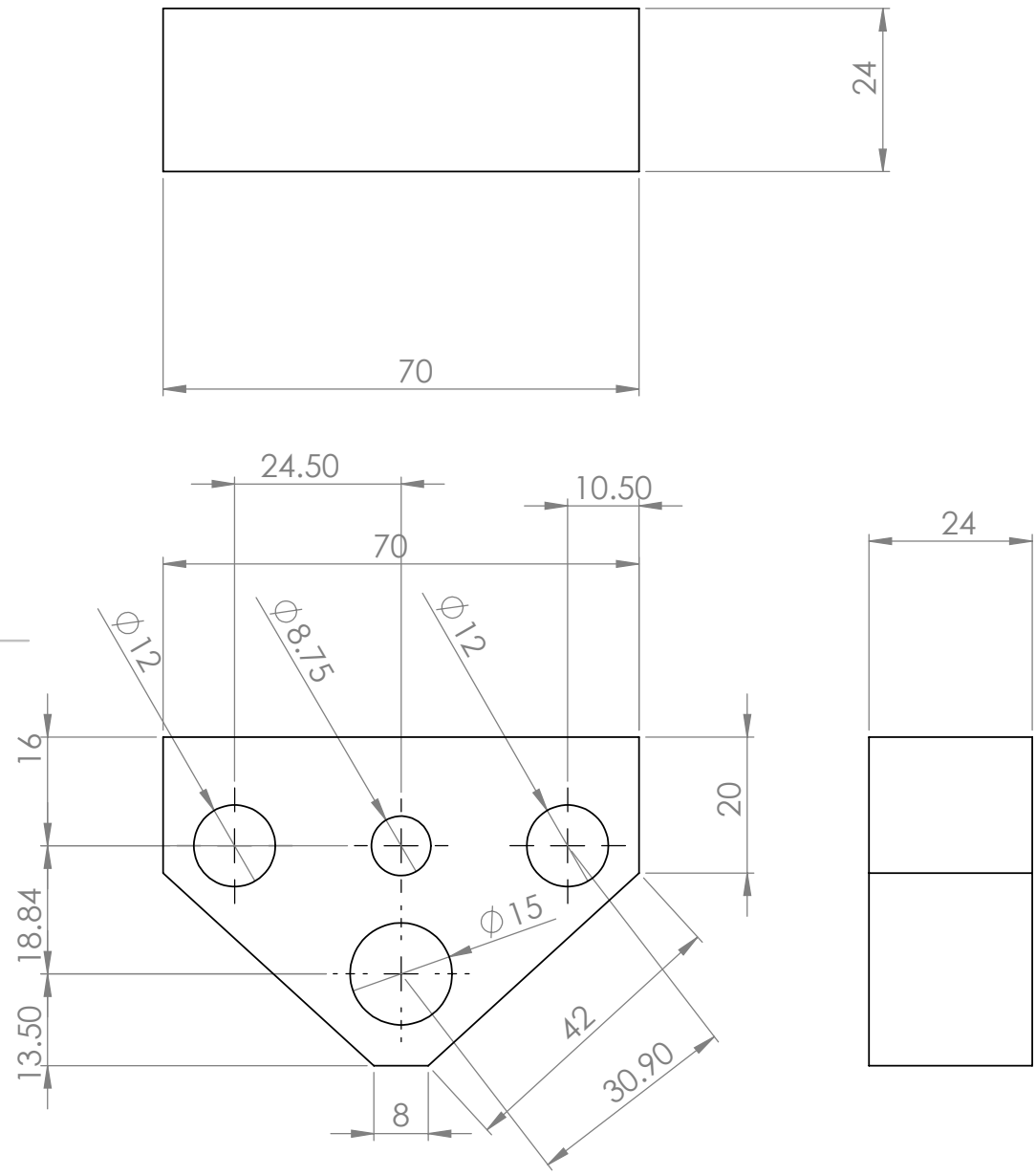
DWG NO. Assem131215

A4

WEIGHT:

SCALE:1:10

SHEET 5 OF 12



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:	DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING / REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

PART 5 (LIFTER)

MATERIAL:

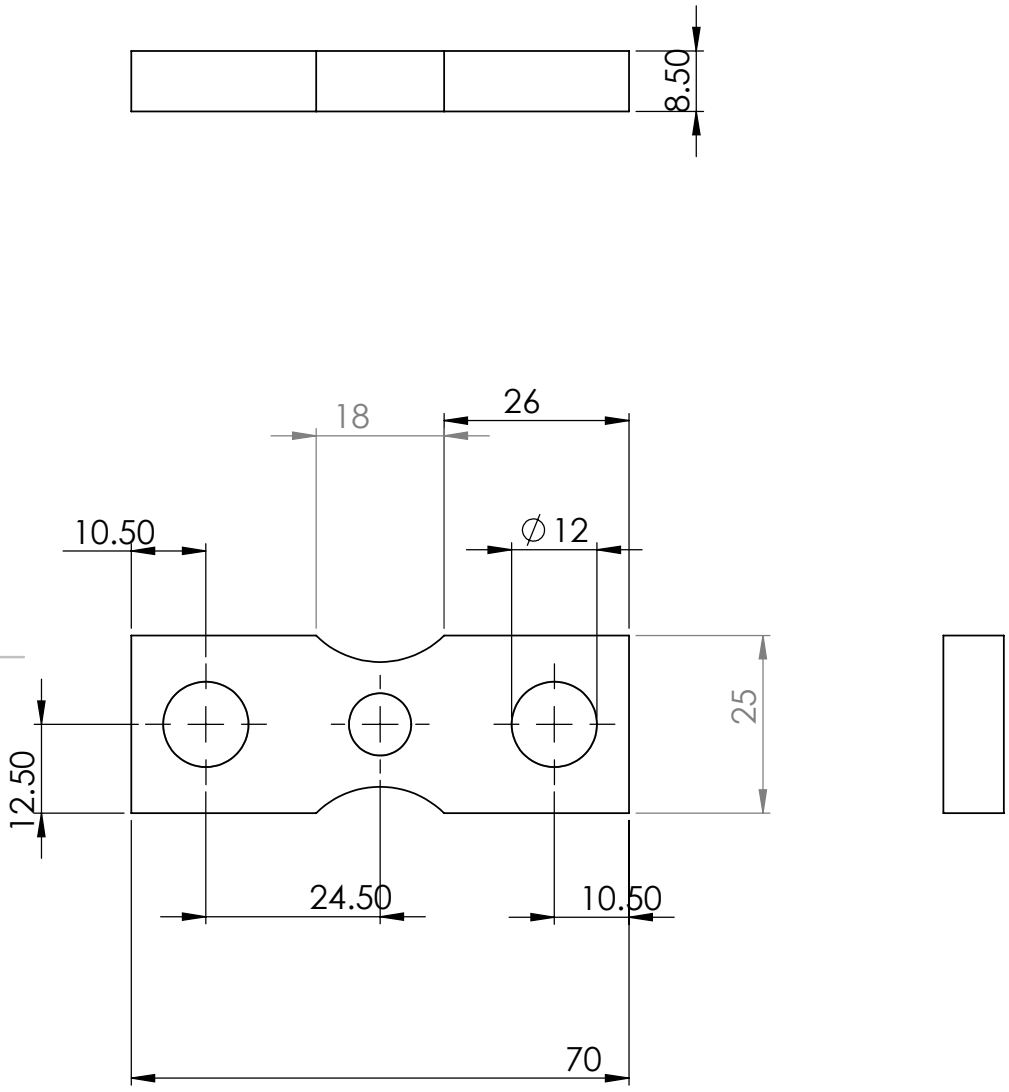
DWG NO. Assem131215

A4

WEIGHT:

SCALE:1:10

SHEET 6 OF 12



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:	DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING / REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

PART 6

MATERIAL:

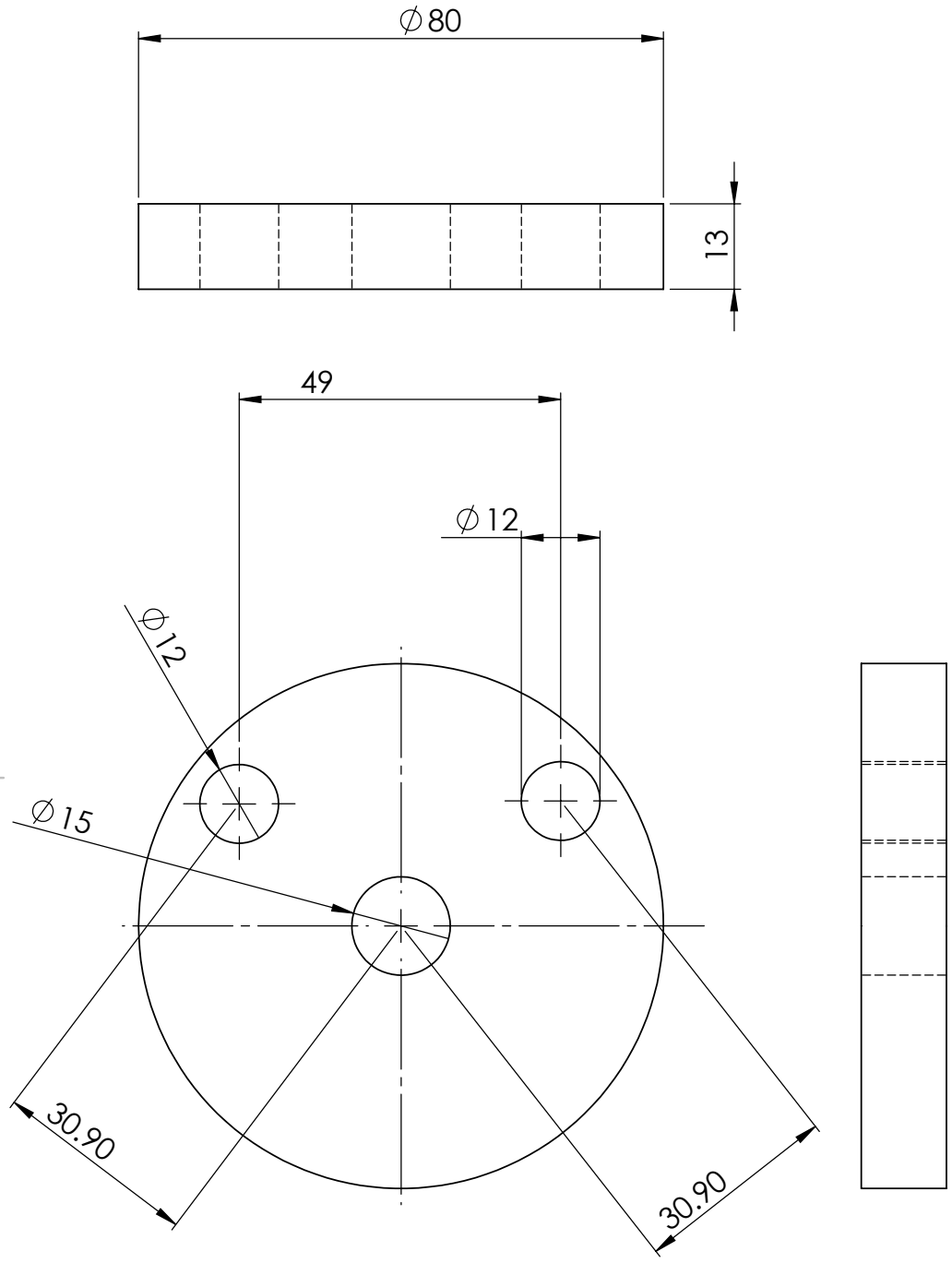
DWG NO. Assem131215

A4

WEIGHT:

SCALE:1:10

SHEET 7 OF 12



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:	DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING / REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

PART 7

MATERIAL:

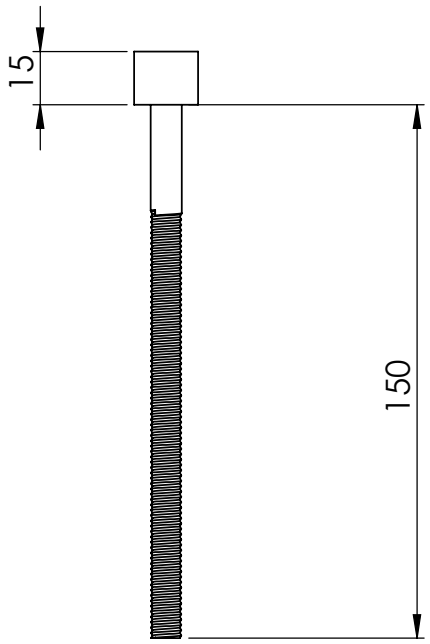
DWG NO. Assem131215

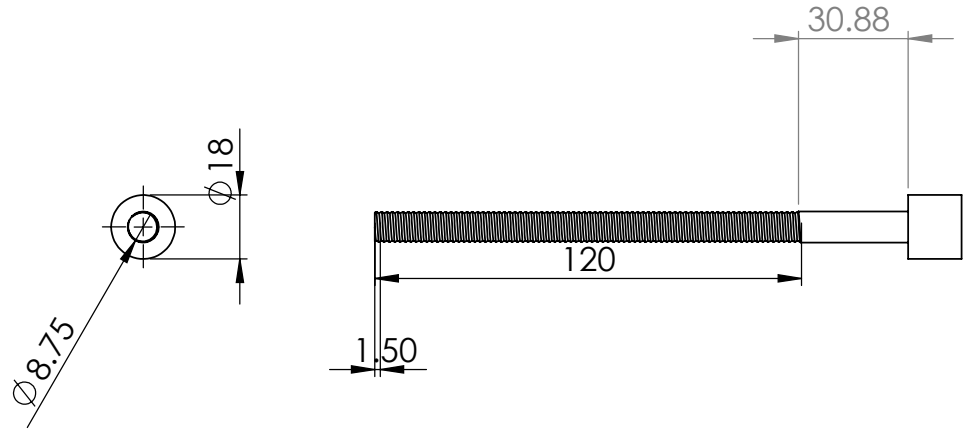
A4

WEIGHT:

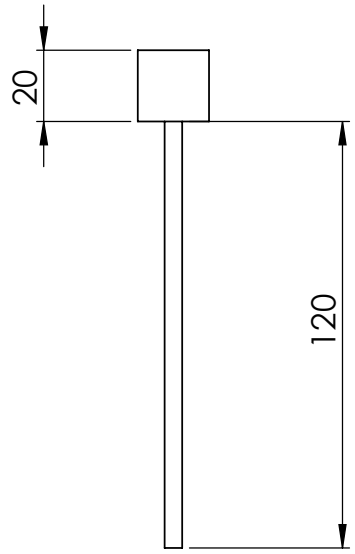
SCALE:1:10

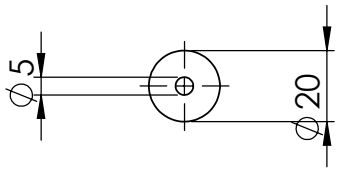
SHEET 8 OF 12

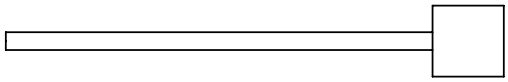




UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:		DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION	
	NAME	SIGNATURE	DATE	PART 8		
DRAWN						
CHK'D						
APPV'D						
MFG						
Q.A				MATERIAL:	DWG NO. Assem131215	A4
				WEIGHT:	SCALE:1:10	SHEET 9 OF 12







UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:	DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING / REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

PART 9

MATERIAL:

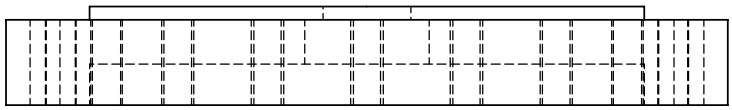
DWG NO. Assem131215

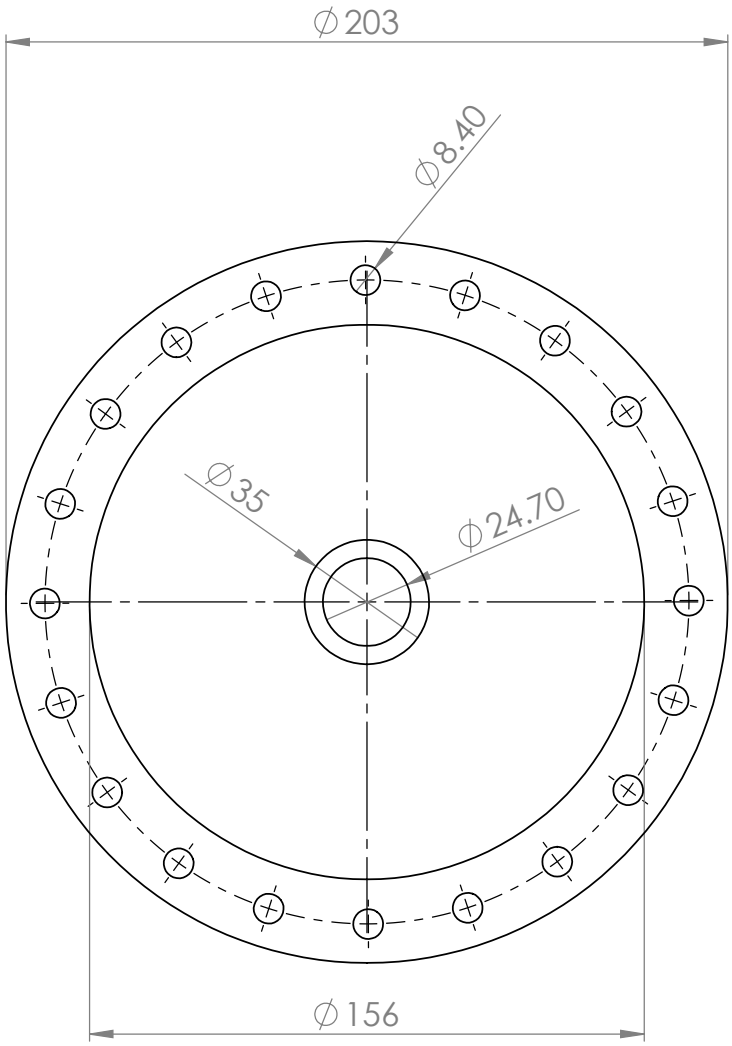
A4

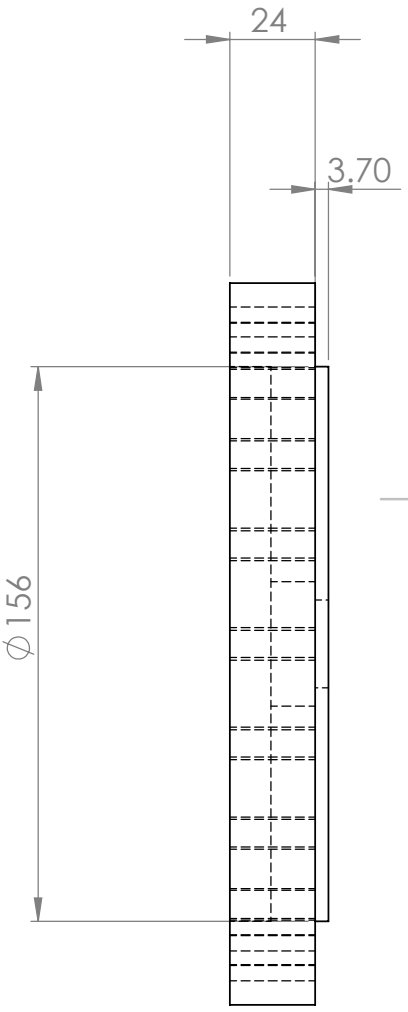
WEIGHT:

SCALE:1:10

SHEET 10 OF 12







UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:	DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING / REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

PART 10

MATERIAL:

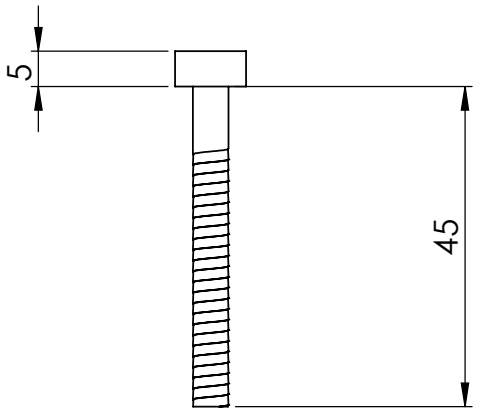
DWG NO. Assem131215

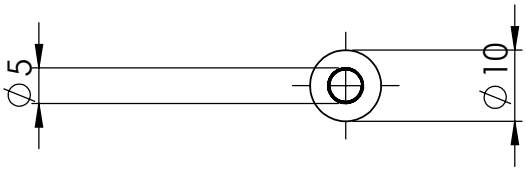
A4

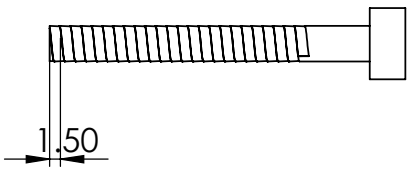
WEIGHT:

SCALE:1:10

SHEET 11 OF 12







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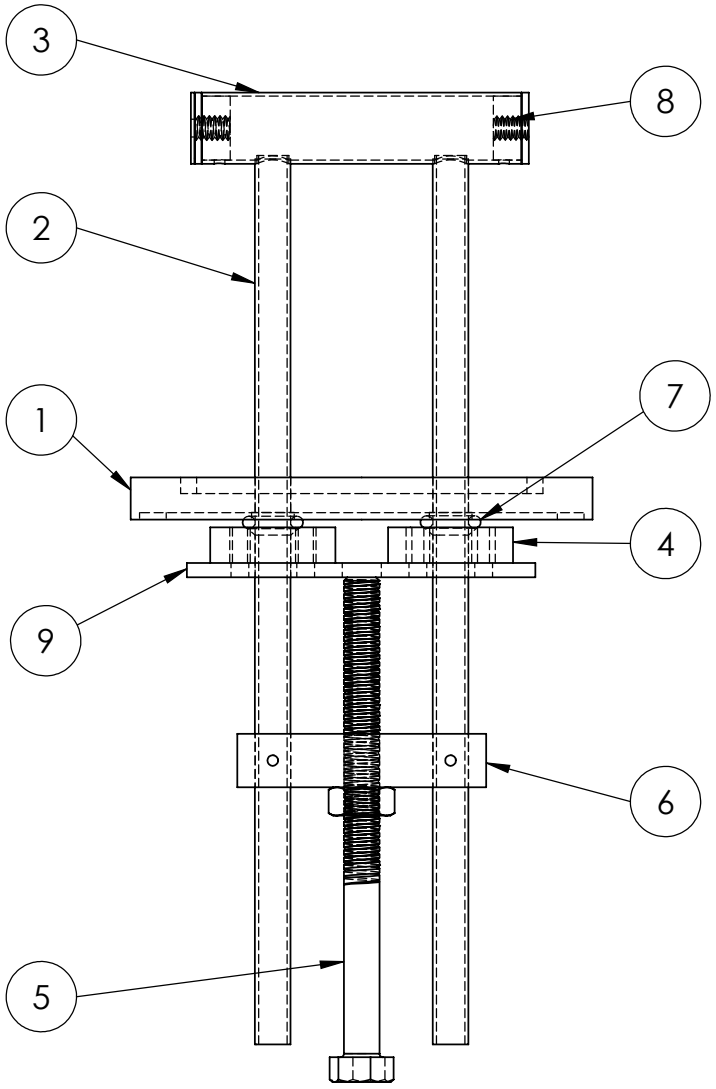
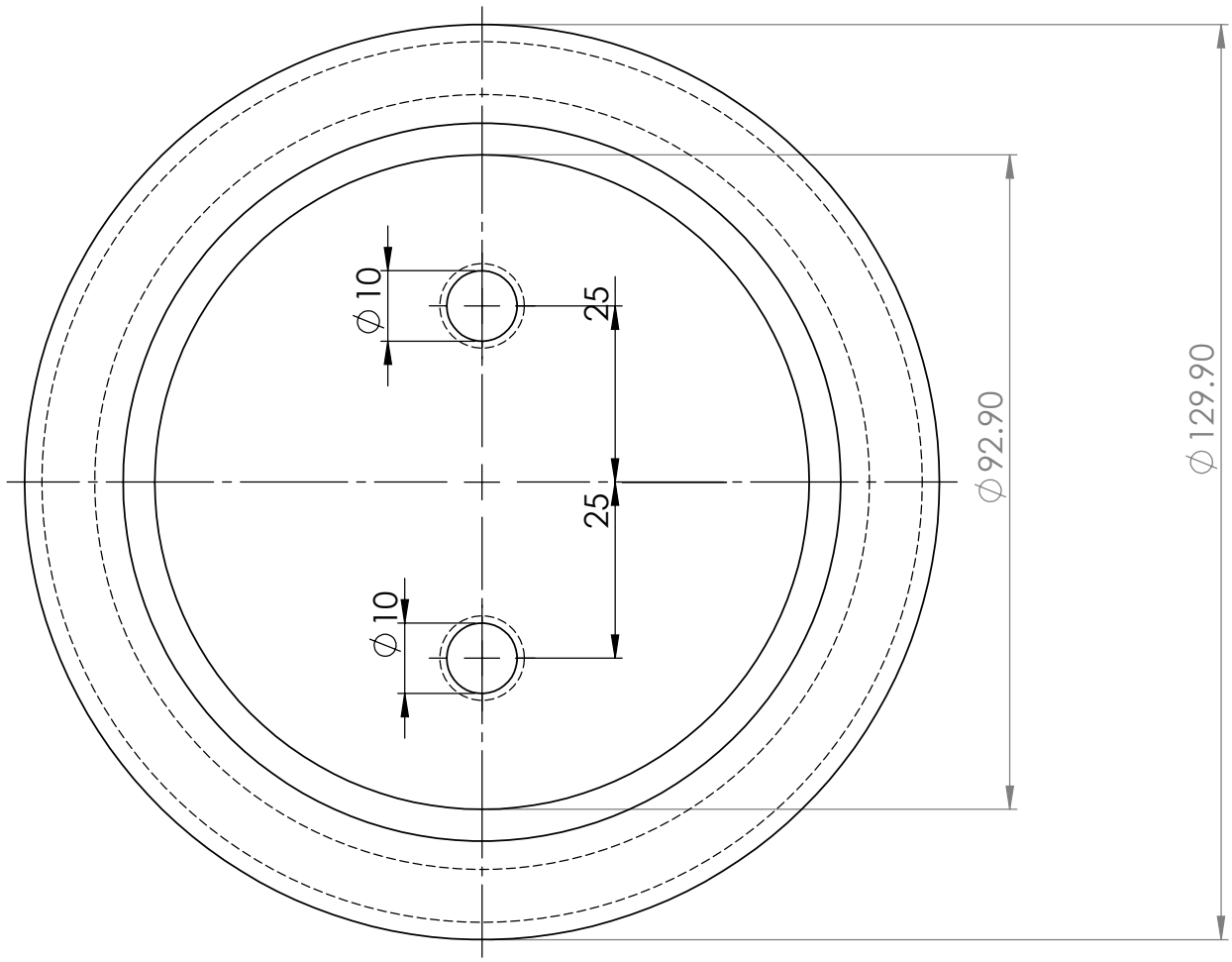
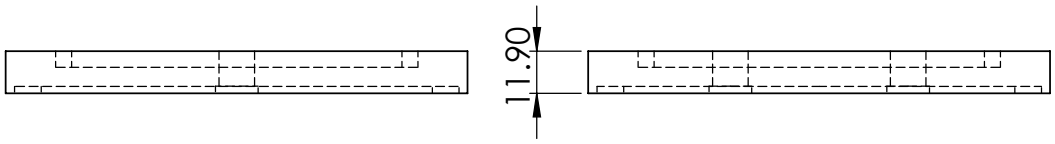
	NAME	SIGNATURE	DATE	PART 11 (X3)		
DRAWN						
CHK'D						
APPV'D						
MFG						
Q.A				MATERIAL:	DWG NO. Assem131215	A4
				WEIGHT:	SCALE:1:10	SHEET 12 OF 12

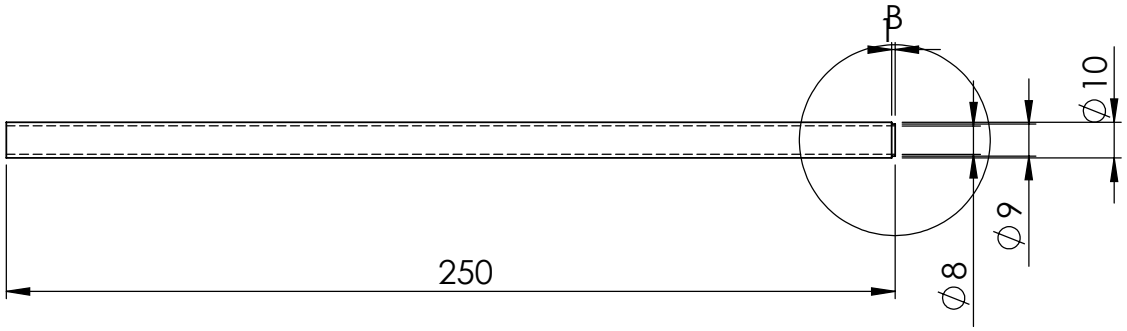


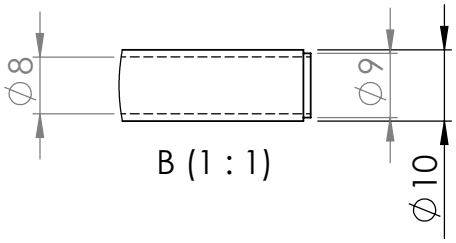
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:		FINISH:				DEBUR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION
	NAME	SIGNATURE	DATE				GAS STRIPPER SYSTEM	
DRAWN								
CHK'D								
APPV'D								
MFG								
Q.A				MATERIAL:			DWG NO. GASSTRIPPERISOK100150119	A4
				WEIGHT:			SCALE:1:5	SHEET 1 OF 10

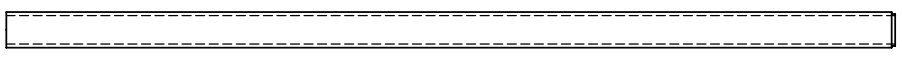




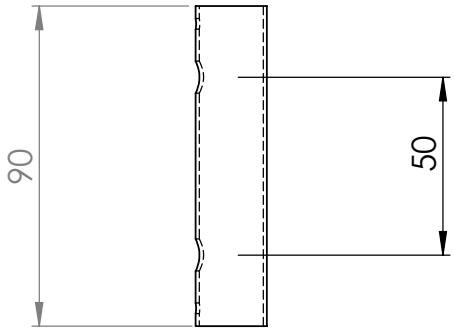
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:		FINISH:			DEBUR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION
	NAME	SIGNATURE	DATE			PART 1 (FLANGE)	
DRAWN							
CHK'D							
APPV'D							
MFG							
Q.A				MATERIAL:		DWG NO. GASSTRIPPERISOK100150119	A4
				WEIGHT:		SCALE:1:5	SHEET 2 OF 10

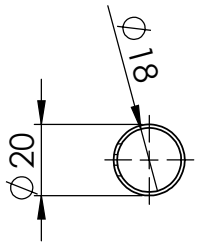


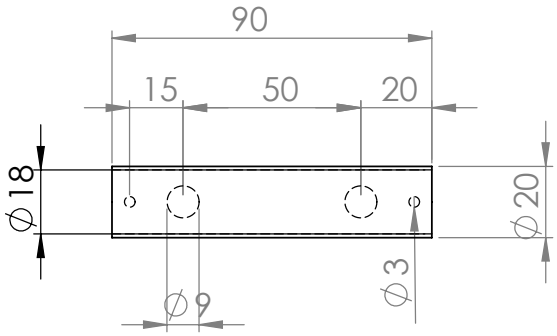




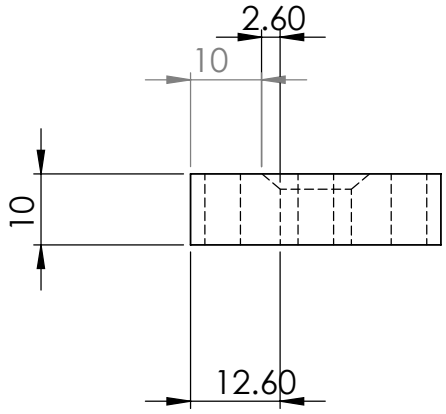
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:		FINISH:			DEBUR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION
	NAME	SIGNATURE	DATE			PART 2 (GAS INSERTING TUBE) (X2)	
DRAWN							
CHK'D							
APPV'D							
MFG							
Q.A				MATERIAL:		DWG NO. GASSTRIPPERISOK100150119	A4
				WEIGHT:		SCALE:1:5	SHEET 3 OF 10

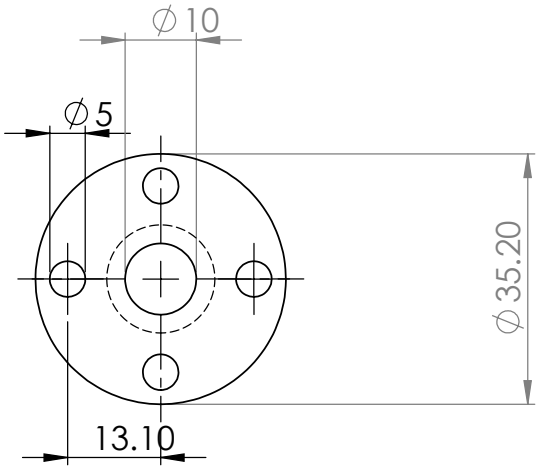


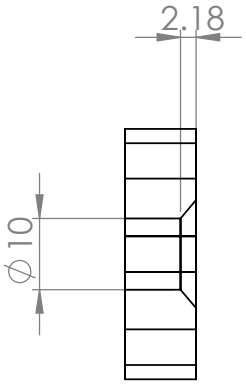




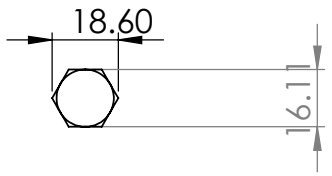
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:		DEBUR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION	
	NAME	SIGNATURE	DATE	PART 3 (STRIPPER TUBE)		
DRAWN						
CHK'D						
APPV'D						
MFG						
Q.A				MATERIAL:	DWG NO. GASSTRIPPERISOK100150119	A4
				WEIGHT:	SCALE:1:5	SHEET 4 OF 10

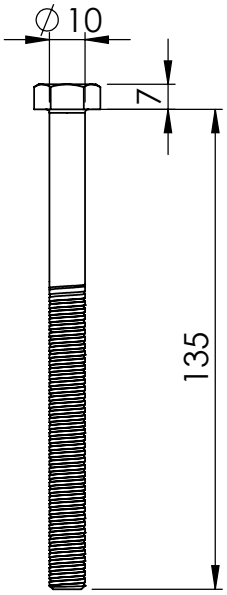


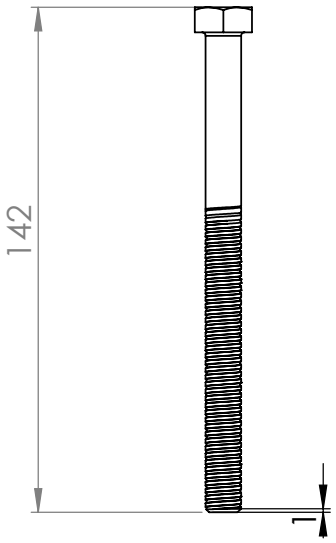




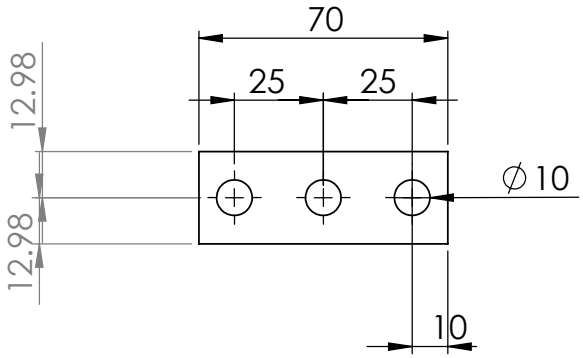
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:		FINISH:			DEBUR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION
	NAME	SIGNATURE	DATE			PART 4 (X2)	
DRAWN							
CHK'D							
APPV'D							
MFG							
Q.A				MATERIAL:		DWG NO. GASSTRIPPERISOK100150119	A4
				WEIGHT:		SCALE:1:5	SHEET 5 OF 10

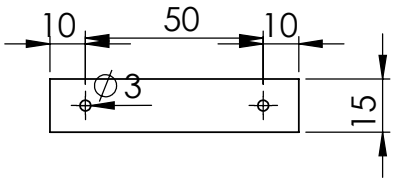


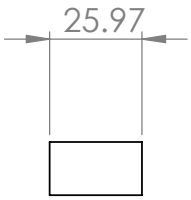




UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:		DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION		
	NAME	SIGNATURE	DATE	PART 5			
DRAWN							
CHK'D							
APPV'D							
MFG							
Q.A				MATERIAL:	DWG NO. GASSTRIPPERISOK100150119	A4	
				WEIGHT:	SCALE:1:5	SHEET 6 OF 10	







UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:	DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING / REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

PART 6

MATERIAL:

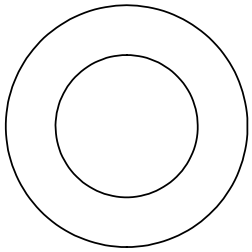
DWG NO. GASSTRIPPERISOK100150119

A4

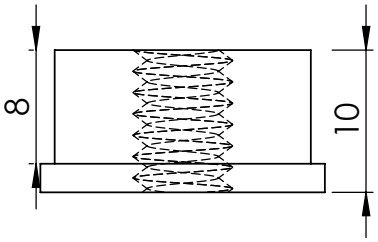
WEIGHT:

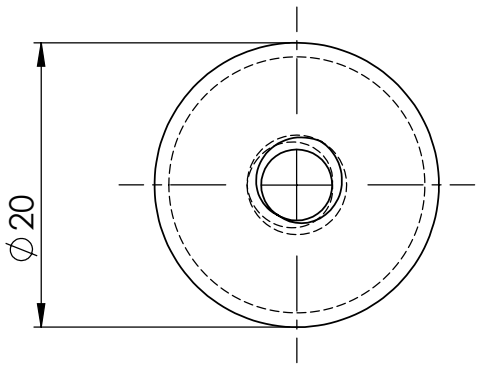
SCALE:1:5

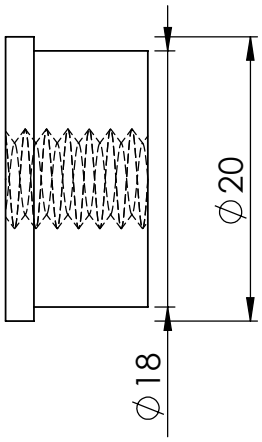
SHEET 7 OF 10



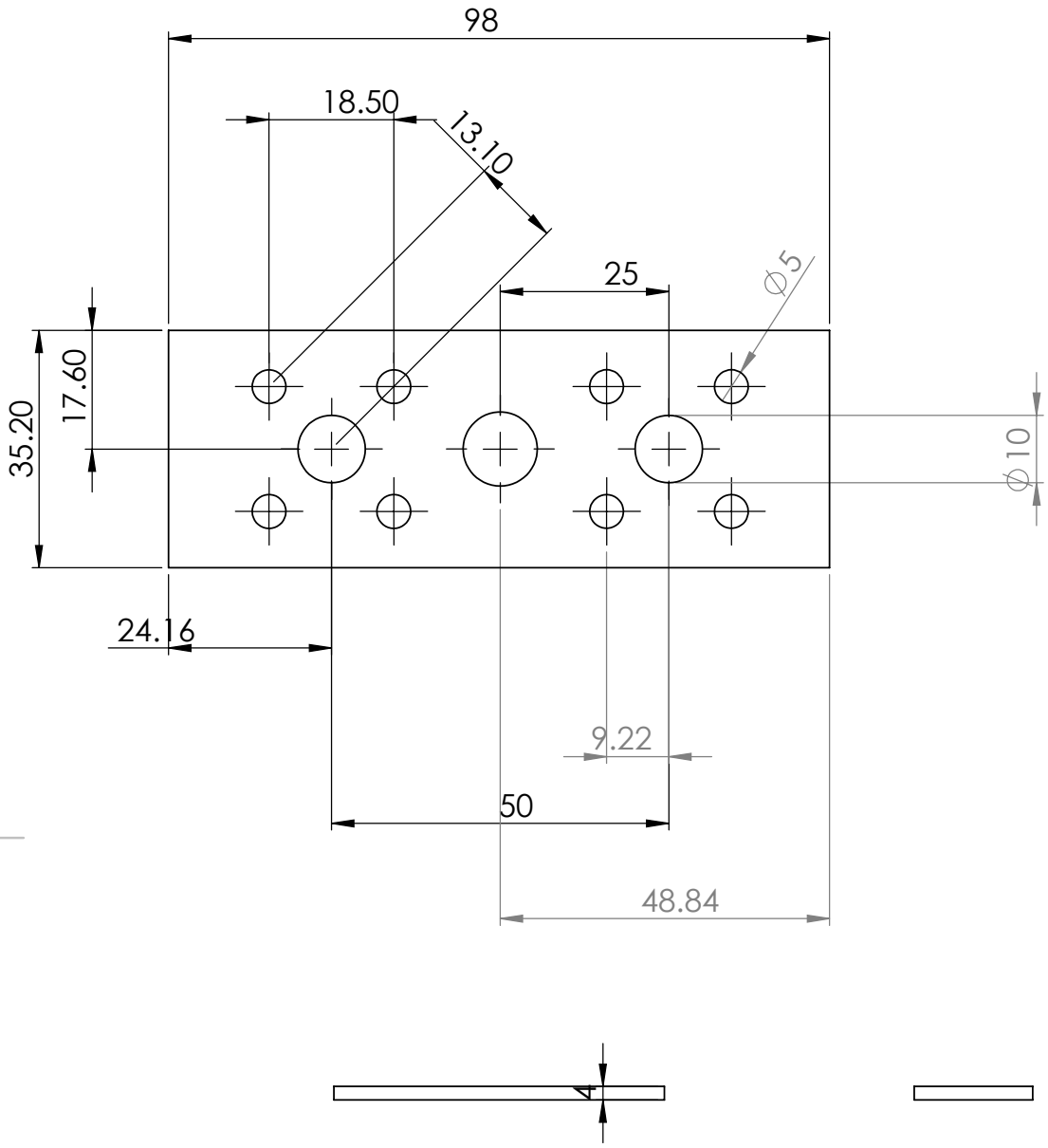
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:		FINISH:		DEBURR AND BREAK SHARP EDGES		DO NOT SCALE DRAWING	REVISION
	NAME	SIGNATURE	DATE			PART 7 (O-RING) (X2)	
DRAWN							
CHK'D							
APPV'D							
MFG							
Q.A				MATERIAL:		DWG NO. GASSTRIPPERISOK100150119	A4
				WEIGHT:		SCALE:1:5	SHEET 8 OF 10







UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:		FINISH:			DEBUR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION
	NAME	SIGNATURE	DATE			PART 8	
DRAWN							
CHK'D							
APPV'D							
MFG							
Q.A				MATERIAL:		DWG NO. GASSTRIPPERISOK100150119	A4
				WEIGHT:		SCALE:1:5	SHEET 9 OF 10



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Παράρτημα Β΄

Διεθνείς δημοσιεύσεις

Β΄.1 Άρθρα σε επιστημονικά περιοδικά

Determination of the solid angle and response function of a hemispherical spectrograph with injection lens for Auger electrons emitted from long lived projectile states

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We present SIMION 8.1 Monte Carlo type simulations of the response function and detection solid angle for long lived Auger states (lifetime $\tau \sim 10^{-9} - 10^{-5}$ s) recorded by a hemispherical spectrograph with injection lens and position sensitive detector used for high resolution Auger spectroscopy of ion beams. Also included in these simulations for the first time are kinematic effects particular to Auger emission from fast moving *projectile* ions such as line broadening and solid angle limitations allowing for a more accurate and realistic line shape modeling. Our results are found to be in excellent agreement with measured electron line shapes of both long lived $1s2s2p\,^4P$ and prompt Auger projectile states formed by electron capture in collisions of 25.3 MeV F^{7+} with H_2 and 12.0 MeV C^{4+} with Ne recorded at 0° to the beam direction. These results are important for the accurate evaluation of the $1s2s2p\,^4P/^2P$ ratio of K-Auger cross sections whose observed non-statistical production by electron capture into He-like ions, recently a field of interesting interpretations, awaits further resolution. © *2015 AIP Publishing LLC.* [http://dx.doi.org/10.1063/1.4917274]

I. INTRODUCTION

Over the last few decades, considerable progress has been made in obtaining information on both the atomic structure and collision dynamics of multiply excited atomic states using high resolution Auger electron spectroscopy.[1,2] This interest has been generated to a large degree in the fields of plasma physics, thermonuclear fusion research, and astrophysics where the collisional properties of highly stripped ions play an important role. The determination of highly accurate excitation energies, transition rates, and lifetimes combined with production cross section information obtained from line intensity measurements leads to a better overall understanding of the dominant processes at play. A persistent problem in such measurements is the determination of the contribution from metastable states to the measured Auger electron yields due to their inherent long lifetime. Indeed, in so called "zero-degree" measurements, where the electron spectrometer lies in the direct path of the ion (and the electrons are measured at 0° with respect to the beam direction), the excited metastable projectile states decay all along its path towards the spectrometer (and even inside the spectrometer), and thus, the overall electron detection solid angle varies with the position of electron emission. This situation can result in a considerable correction to the measured 0° electron yield. So far in the literature, this correction has been treated primarily by determining a purely geometrical[1,3–5] solid angle correction factor. Such an approach can only be, in principle, applied to spectrometers that do not have focusing elements at their entrance. However, modern spectrographs equipped with a focusing/pre-retardation entry lens and position sensitive detector (PSD) do not allow for such a straightforward geometrical correction treatment of the solid angle due to the more complex input lens optics and has not been attempted to date.

In this report, we present a Monte Carlo type approach within the SIMION 8.1[6] charged particle optics simulation environment to treat the problem of the accurate determination of the solid angle correction factor for a hemispherical deflector analyzer (HDA) with injection lens[7–10] and PSD. We have been using such a spectrograph over the last decade and now turn to the determination of electron yields from excited metastable ion projectile states as in the on-going APAPES project[11] where such a correction will be crucial. Here, we re-examine and extend the existing geometrical approaches (applied to conventional slit spectrometers) to also include spectrographs with a focusing/pre-retardation entry lens. In addition, we also include important rest-frame-to-laboratory kinematic considerations, previously not considered, but here shown to be important in the accurate determination of the measured line shape with a HDA. As a stringent test of our approach, we reproduce in remarkable good agreement the Auger line shape of the long lived $1s2s2p\,^4P$ (^4P for short) state recorded in older measurements by our spectrograph in 25.3 MeV $F^{7+} + H_2$[12,13] and in new 12.0 MeV $C^{4+} + Ne$ measurements presented here for the first time. Our approach will be used in ongoing measurements with He-like ionic beams of pure $1s^2\ ^1S$ ground state and mixed ($1s^2\ ^1S$, $1s2s\ ^3S$) ground and metastable states, to correctly determine the measured electron yield of the ^4P state formed by electron capture and account for the ratio $R = {}^4P/{}^2P$ of cross sections. This ratio, has been of recent interest,[5,14–17] as large departures from the expected statistical value of $R = 2$ has been reported

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lending themselves to various explanations as to possible mechanisms involved.

II. KINEMATIC CONSIDERATIONS

We include here, a brief summary of electron kinematic transformations for electron emission from moving ionic emitters. We also present, for the first time, our theoretical results using more accurate equations derived from the special relativistic consideration[18] of these transformations which can result in shifts of a few eV in the position of Auger lines in typical MeV/u ion beams and important in high resolution measurements.

Auger electrons emitted from scattered projectiles are kinematically influenced. A detailed analysis of the general electron kinematic effects can be quite complicated.[1,19] However, for the case of energetic collisions of a few MeV/u or larger, projectile ions are scattered through very small angles (~milliradian), resulting in negligible effects both on the energy loss and the projectile electron trajectories. In this case, a simple velocity vector addition model is sufficient for the determination of the kinematic effects. Thus, the velocity $\mathbf{v}$ of the Auger electron in the laboratory frame is obtained by adding the projectile velocity $\mathbf{V}_p$ to the velocity $\mathbf{v}'$ of the electron in the projectile rest frame as shown in Fig. 1. Denoting with prime, quantities in the projectile rest frame, the electron kinetic energy ε in the laboratory frame can be related to the corresponding rest frame electron kinetic energy ε' as

$$\varepsilon = \varepsilon' + t_p + 2\sqrt{\varepsilon' t_p}\,\cos\theta' \tag{1}$$

or its more accurate relativistic counterpart

$$\varepsilon = \gamma_p\varepsilon' + t_p + \sqrt{(1+\gamma')\varepsilon'(1+\gamma_p)t_p}\,\cos\theta', \tag{2}$$

where $t_p = \frac{m}{M_p}E_p$ is the reduced projectile energy known also as the *cusp* electron energy (electrons isotachic to the projectile ion). E_p and M_p are the kinetic energy and mass of the projectile, respectively, while m is the electron mass and $\gamma_p(=1+\frac{t_p}{mc^2})$ and $\gamma'(=1+\frac{\varepsilon'}{mc^2})$ are the usual relativistic γ-parameters for speeds V_p and v', respectively. Clearly, Eq. (2) can be seen to go to its classical limit Eq. (1), when γ_p and γ' go to 1.

It is practical to express the relation between the electron kinetic energies in the laboratory and rest frame ε and ε' as a function of the *laboratory* emission angle θ. Applying simple trigonometric rules to the geometry of Fig. 1, the laboratory kinetic energy ε can be written as[1]

$$\varepsilon_\pm(\theta) = \varepsilon'(\zeta_p'\cos\theta \pm \sqrt{1-\zeta_p'^2\sin^2\theta}\,)^2$$

$$(\zeta_p' > 1,\ 0 \le \theta \le \sin^{-1}\left(\frac{1}{\zeta_p'}\right)), \tag{3}$$

$$\varepsilon(\theta) = \varepsilon_+(\theta) \qquad (\zeta_p' \le 1,\ 0^\circ \le \theta \le 180^\circ), \tag{4}$$

or its more accurate relativistic counterpart (readily derived from energy-momentum 4-vector Lorentz transformation algebra[18])

$$\varepsilon_\pm(\theta) = \left[\sqrt{1+(\gamma'^2-1)\chi_{p_\pm}^2} - 1\right] mc^2$$

$$\left(\zeta_p' > 1,\ \ 0 \le \theta \le \sin^{-1}\left[\frac{1}{\sqrt{1+\gamma_p^2(\zeta_p'^2-1)}}\right]\right), \tag{5}$$

$$\varepsilon(\theta) = \varepsilon_+(\theta) \qquad (\zeta_p' \le 1,\ 0^\circ \le \theta \le 180^\circ), \tag{6}$$

where $\chi_{p_\pm}$ is given by

$$\chi_{p_\pm} \equiv \chi_{p_\pm}(\zeta_p', \gamma_p, \theta)$$

$$= \frac{\gamma_p\left[\zeta_p'\,\cos\,\theta \pm \sqrt{1-\sin^2\theta\left(1+\gamma_p^2(\zeta_p'^2-1)\right)}\right]}{\cos^2\theta + \gamma_p^2\sin^2\theta}, \tag{7}$$

with $\zeta_p' \equiv V_p/v'$ a convenient dimensionless parameter.[1] Equation (5) can be brought to the form

$$\varepsilon_\pm(\theta) = \left\{\sqrt{\left[1+\left(\frac{\varepsilon'}{2mc^2}\right)(\gamma'+1)\chi_{p_\pm}^2\right]^2 - \frac{1}{4}(\gamma'^2-1)^2\chi_{p_\pm}^4} - 1\right\} mc^2, \tag{8}$$

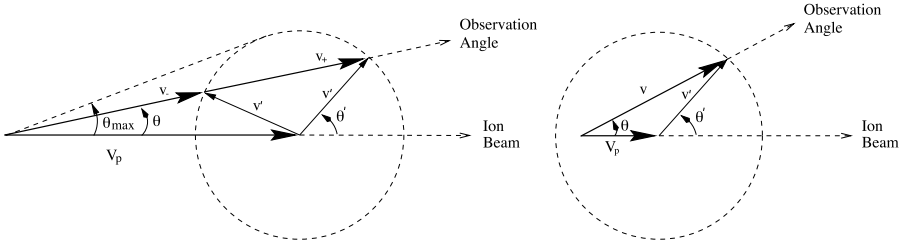

FIG. 1. Velocity addition diagrams. The electron velocity $\mathbf{v}'$ in the projectile rest frame is transformed to the laboratory frame according to the vector addition rule $\mathbf{v} = \mathbf{V}_p + \mathbf{v}'$, where $\mathbf{V}_p$ is the velocity of the projectile (emitter). [*Left*] $V_P > v'$ leading to a maximum possible θ. [*Right*] $V_P < v'$, where all angles θ now become possible.

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where we have used $(\gamma'^2 - 1) = (\gamma' + 1)(\gamma' - 1) = \left(\frac{\varepsilon'}{mc^2}\right)(\gamma' + 1)$. Again, Eq. (8) can be seen to go to its classical limit Eq. (3), when γ_p and γ' go to 1.

As illustrated in Fig. 1, for *fast* emitters ($\zeta'_p > 1$ or equivalently $t_p > \varepsilon'$), there can be two possible solutions $\varepsilon_\pm$ (with corresponding velocities $v_\pm$) for the *same* laboratory emission angle θ, while for *slow* emitters ($\zeta'_p \leq 1$ or equivalently $t_p \leq \varepsilon'$), there is *only one* solution. For fast emitters, the constraint $1 - \zeta'^2_p \sin\theta^2 \geq 0$ in Eq. (3) results in a restriction on the emission angle θ to within a maximum value

$$\theta_{max} = \sin^{-1}\left(\frac{1}{\zeta'_p}\right) \tag{9}$$

or its more accurate relativistic counterpart resulting from Eq. (5),

$$\theta_{max} = \sin^{-1}\left[\frac{1}{\sqrt{1 + \gamma_p^2(\zeta'^2_p - 1)}}\right]. \tag{10}$$

We shall use the more accurate relativistic form for $\varepsilon_\pm$ and θ_{max} in our SIMION Monte Carlo simulations in Sec. IV.

III. THE SOLID ANGLE CORRECTION FACTOR—G_τ

Projectile Auger transitions can be distinguished into *prompt* or *metastable* depending on whether the *decay length* $z_e \equiv V_p\tau$ is much smaller or comparable to the length of the detection geometry L, where τ is the lifetime of the state giving rise to the observed Auger line. Most Auger states can be considered prompt since $\tau \sim 10^{-6}$ ns and for $V_p \sim 4 - 30$ mm/ns (a 1 MeV/u projectile has a speed of ~13.89 mm/ns) gives $z_e \sim 4 \times 10^{-6} - 30 \times 10^{-6}$ mm therefore decaying well within the target volume. However, metastable states with lifetimes $\tau > 10$ ns give rise to substantially larger decay lengths $z_e > 40$ mm and therefore contribute over a considerable length of the projectile trajectory even well *outside* the target volume. Thus, for prompt decays, Auger electrons are emitted from a small well defined volume and their detection solid angle depends mostly on geometrical parameters of the experimental setup. For metastable states, however, the emission is not localized and the effective solid angle has to rely on model calculations including the decay lifetimes independently obtained from atomic structure calculations or measurements.

We next consider the calculation of the detection solid angle for each of the two cases. A typical geometry is shown in Fig. 2. The target area consists of a gas cell of length L_c within which the excitation of the projectile ion takes place by collision with a target atom. At distance s_0 lies the entrance of the spectrometer here consisting of an injection lens, a hemispherical deflector analyzer, and a 2-dimensional PSD.[20] The spectrograph lies in the direct path of the ion, so the ion traverses the lens, part of the HDA, exits from a special exit aperture at the back of the HDA, and is collected in a Faraday cup (FC). This particular observation angle $\theta_{obs} = 0°$ is chosen since kinematic line broadening effects are minimized at this

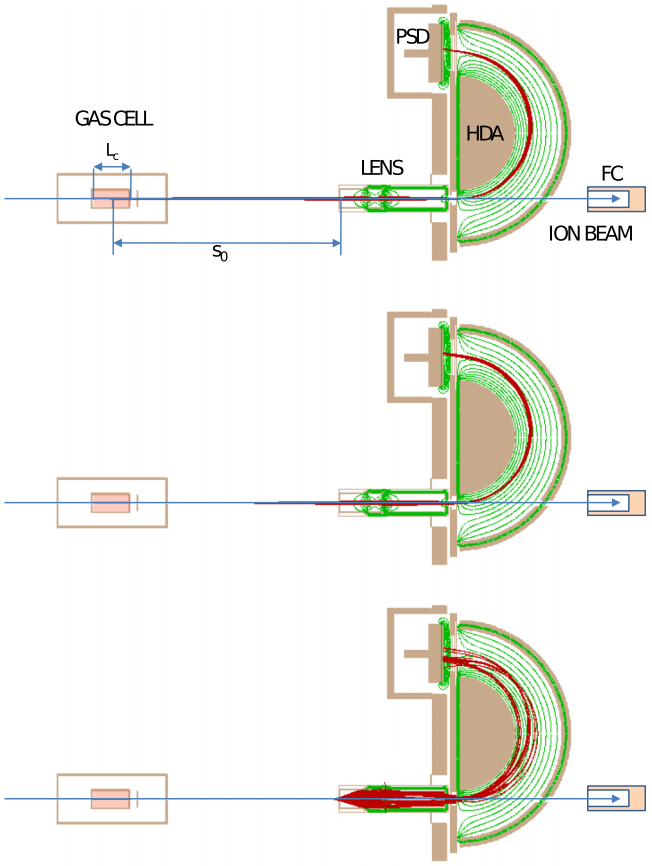

FIG. 2. Schematic of the simulated experimental setup. The projectile ions are excited in collisions inside the gas cell of length L_c. Electrons emitted from the excited ions are focused by the lens into the HDA, then analyzed according to their laboratory energy ε, and finally refocused on to the PSD. The projectile ions continue through the spectrometer unaffected and are collected in a FC. Prompt states (top) decay fast, emitting Auger electrons only from within the gas cell, and therefore, their acceptance solid angle is limited by the lens entry aperture a distance s_0 away. Metastable states (middle and bottom), however, decay much slower emitting electrons along the ion's trajectory all the way through the lens and HDA. Close to the lens entry, solid angle effects become considerable. Many electrons are filtered out by the lens, but some do reach the PSD contributing significantly to the kinematic broadening of the observed line shape. Their contributions are assessed here through SIMION simulations.

angle. The technique has become known as zero-degree Auger projectile spectroscopy (ZAPS).[1]

In the case of long-lived projectile Auger states J, one faces the difficulty that part of the measured electron yield $N_J^e(\varepsilon)$ originates from emission points outside the target cell lying all along the path between the cell and the spectrometer resulting in a very different effective solid angle $\Delta\Omega_J$ than for the practically point source solid angle $\Delta\Omega_0$ in the case of prompt Augers. For such a metastable state, we may set the effective solid angle, $\Delta\Omega_J = G_{\tau_J}\Delta\Omega_0$, thus defining the correction factor G_{τ_J}.

The most commonly encountered metastable state in ZAPS is the $1s2s2p\,^4P_J$ state with $J = 1/2, 3/2, 5/2$. ^4P_J lifetimes τ_J depend on the total angular momentum component J and are given in Table I for the carbon and fluorine atoms. For Li-like oxygen and fluorine ^4P states in 0.5 -2 MeV/u collisions, the effect of the long lifetimes gave $G_{\tau_J} \sim 1.5 - 1.7$ showing this to be a substantial correction

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TABLE I. Theoretical parameters for the $1s2s2p\ ^4P_J$ states of F^{6+} and C^{3+} ions: projectile energies E_p, lifetimes τ_J, Auger yields ξ_J, correction factor G_{τ_J}, J-averaged correction factor G_τ, statistical factors a_J, and Auger energies ε'. Also listed is the ratio $V_p\tau_J/L$. Note that $L = 295$ mm for the case of 25.3 MeV, while $L = 320$ mm for 12.0 MeV as they correspond to two different experimental setups (s_0 = 264 mm and s_0 = 289 mm, correspondingly) of the otherwise same spectrograph.

State	E_p (MeV)	J	τ_J (ns)	ξ_J	$V_p\tau_J/L$	G_{τ_J}	a_J	ξ	ε' (eV)	G_τ	Reference
		1/2	0.57	0.93	0.031	1.09	1/6				26
		3/2	1.85	0.42	0.101	1.43	2/6	0.79	529.8	3.11	26
		5/2	15.90	0.99[a]	0.864	4.22	3/6				24
F^{6+}	25.3										
		1/2	0.67	0.91	0.036	1.11	1/6				22,27
		3/2	2.15	0.27	0.117	1.56	2/6	0.74	529.8	3.24	22,27
		5/2	16.16	0.99	0.878	4.20	3/6				22,27
		1/2	3.01	1.00	0.131	1.74	1/6				26
		3/2	9.10	0.97	0.395	4.48	2/6	0.99	229.64	3.03	26
		5/2	65[a]	0.99[a]	2.822	2.51	3/6				24
C^{3+}	12.0										
		1/2	3.70	0.99	0.161	2.10	1/6				22,27
		3/2	13.19	0.94	0.573	4.95	2/6	0.98	229.64	2.73	22,27
		5/2	117.20	1.00	5.088	1.56	3/6				22,27

[a]Extrapolated.

in measurements using two-stage parallel plate analyzers (2PPA).[3] The correction factor G_{τ_J} computed below follows along the lines of the treatment of Zouros and Lee[1,3]—first developed for 2PPA with slits used in ZAPS—with some important modifications applicable to a HDA with injection lens and PSD. A slightly different approach by Tanis *et al.* for a 2PPA leads to the same formula.[21]

The number of projectiles excited to the metastable state J in collisions with a differential target length element dz' (see Fig. 3) is

$$dN_0^J = N_0\sigma_J n dz' \quad (0 \le z' \le L_c), \tag{11}$$

where σ_J is the *production* cross section for *direct* (e.g., direct capture, excitation, or ionization of the corresponding impinging He-like, Li-like, or Be-like ion beam) populating the ^4P_J state in the collision with N_0 number of ions impinging on the target of areal density ndz' (#atoms/cm^2). Following excitation at $z'(z = 0)$, within the time $t = z/V_p$ and $t + dt$ later, dN_{τ_J} metastable states decay

$$dN_{\tau_J} = dN_0^J\left(\frac{e^{-z/V_p\tau_J}}{V_p\tau_J}\right)dz \quad (0 \le z \le L - z'), \tag{12}$$

where τ_J denotes the lifetime of the metastable state with angular momentum J and L is the maximal distance along the ion trajectory over which significant contributions to the overall electron line shape can be made. Its exact value is investigated in the SIMION simulations in Sec. IV. In Fig. 2 is shown a schematic of the experimental setup simulated here.

Assuming electron emission at z, we integrate all electron contributions along the beam trajectory from $z = 0$—the point of excitation—all the way to $z = L - z'$ to obtain the total number of accepted electrons within $d\varepsilon\, d\Omega$, $N^e_{\tau_J}(\varepsilon)\, d\varepsilon\, d\Omega$, as

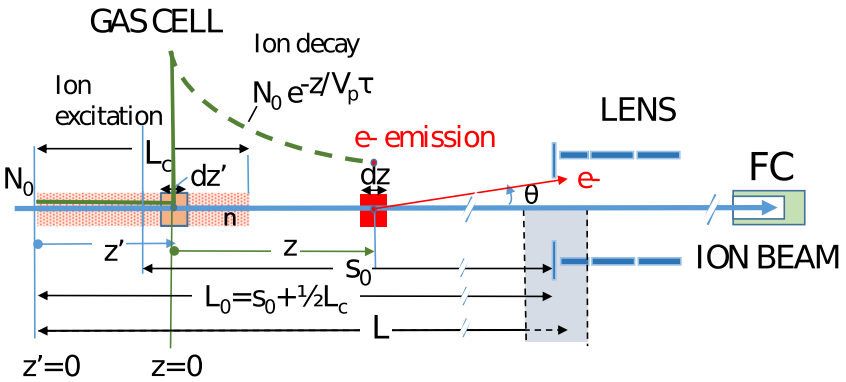

FIG. 3. Schematic of integration region used in Eqs. (11) and (12). N_0 ions (in the initial $1s2s\ ^3S$ state) enter the gas cell (length L_c at distance s_0 from the lens entry) from the left with velocity V_p and get excited (by electron capture in a collision with a target gas atom of density n) between z' and $z'+dz'$ to the $1s2s2p\ ^4P$ state. Due to its long lifetime τ, the excited ionic ^4P state travels a further distance z before it decays emitting an Auger electron at angle θ which enters the lens and is eventually energy analyzed by the HDA (not shown). The ions traverse the entire lens and part of the HDA, exiting at the back of the HDA, and finally collected in a FC used for beam normalization. The length L marks the part of the ion trajectory over which emitted electrons contribute to the ^4P line shape with *non-negligible* intensity as measured by the PSD. The exact value of L (gray area) is determined here by SIMION simulation together with the overall effective detection solid angle $\overline{\Delta\Omega}(L)$ (Eq. (19)). Diagram not to scale.

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follows:

$$N^e_{\tau_J}(\varepsilon)\,d\varepsilon\,d\Omega = N_0 n L_c \sigma_J \xi_J d\varepsilon \left[\frac{1}{L_c}\int_{z'=0}^{L_c} dz' \times \int_{z=0}^{L-z'} dz \frac{e^{-z/V_p\tau_J}}{V_p\tau_J}\Delta\Omega_0(L-z'-z)\right], \quad (13)$$

where ξ_J is the Auger yield, i.e., the probability for the state J to decay through the particular Auger transition giving rise to the corresponding electron.

Since for low-Z ions, the different J components of the $1s2s2p\,^4P$ Auger line cannot be resolved, we may add all J contributions to obtain

$$N^e_\tau(\varepsilon)\,d\varepsilon\,d\Omega = \sum_J N^e_{\tau_J}(\varepsilon) d\varepsilon\,d\Omega \equiv N_0 n L_c \sigma \xi d\varepsilon G_\tau \overline{\Delta\Omega_0}(s_0), \quad (14)$$

where $\sigma = \sum_J \sigma_J$ and we have introduced the J-averaged solid angle correction factor G_τ,

$$G_\tau \equiv \frac{\sum_J a_J \xi_J G_{\tau_J}}{\sum_J a_J \xi_J} = \frac{\sum_J a_J \xi_J G_{\tau_J}}{\xi} = \frac{\sum_J (2J+1)\xi_J G_{\tau_J}(L, V_p\tau_J, s_0, L_c)}{\sum_J (2J+1)\xi_J}, \quad (15)$$

with

$$G_{\tau_J} = G_{\tau_J}(L, V_p\tau_J, s_0, L_c) \equiv \overline{\Delta\Omega_J}(L, V_p\tau_J, L_c)/\overline{\Delta\Omega_0}(s_0, L_c), \quad (16)$$

$$a_J \equiv \sigma_J/\sigma = (2J+1)/\sum_J (2J+1), \quad (17)$$

$$\xi \equiv \sum_J a_J \xi_J. \quad (18)$$

The effective solid angle for the metastable state J averaged over the length of the gas cell is

$$\overline{\Delta\Omega_J}(L, V_p\tau_J, L_c) \equiv \left[\frac{1}{L_c}\int_{z'=0}^{L_c} dz' \int_{z=0}^{L-z'} dz \frac{e^{-z/V_p\tau_J}}{V_p\tau_J}\Delta\Omega_0(L-z'-z)\right], \quad (19)$$

and similarly, for a prompt state,

$$\overline{\Delta\Omega_0}(s_0, L_c) \equiv \left[\frac{1}{L_c}\int_{z'=0}^{L_c} dz' \Delta\Omega_0(L_c/2 + s_0 - z')\right], \quad (20)$$

where the solid angle $\Delta\Omega_0(s)$ for point source emission into the lens entry aperture of radius r at distance s and the corresponding angle θ are given by

$$\cos\theta = \frac{s}{\sqrt{r^2+s^2}}, \quad (21)$$

$$\Delta\Omega_0(s) = 2\pi(1-\cos\theta) = 2\pi\left(1 - \frac{s}{\sqrt{r^2+s^2}}\right). \quad (22)$$

In Eq. (22), we always have $\theta \le \theta_{max}$ given by Eq. (10). For prompt states, the variation in θ is less than 1° in typical setups (e.g., for the current setup $r = 2$ mm, $s_0 = 289$ mm, $L_c = 50$ mm) and thus $\Delta\Omega_0(s_0) = 1.505 \times 10^{-4}$ sr and $\overline{\Delta\Omega_0}(s_0, L_c) = 1.515 \times 10^{-4}$ sr, respectively. The difference is less than 1% and may be neglected. Equation (13) is then just the average of the electron emission probability over the excitation length in the target and along the subsequent decay distance. Typical variations of the solid angle $\Delta\Omega_0(s_0 - z)$, the linear probability density $F_\tau(z) = \exp(-z/V_p\tau)/V_p\tau$, and their product can be seen in Fig. 4.

From Eq. (16), it is clear that G_{τ_J} can be computed directly as the ratio of the effective solid angle of the long lived state (see Eq. (19)) to that of the same state but prompt (Eq. (20)). Here, we evaluate this ratio using the SIMION Monte Carlo approach described in Sec. IV.

The above G_τ correction factor formulation has been widely applied to the case of two-stage parallel plate slit spectrometers traditionally used in ZAPS.[1] In this case, the limiting detection aperture is typically found at the exit slit of the spectrometer, and therefore, the solid angle is very small even for metastable decays. This situation is completely different for single-stage spectrometers with an injection lens at their entrance, such as the HDA, and having a PSD at their exit. In this case, on one hand, the lack of any other defining apertures beyond those found in the lens and HDA entry simplifies any transmission calculations. On the other hand, as already discussed, the injection lens complicates the theoretical determination of L required in the evaluation of the solid angle in Eq. (19). Here, it is determined by SIMION simulations discussed in Sec. IV.

IV. THE SIMION MONTE CARLO APPROACH

As already mentioned in Secs. I–III, the inability to *a priori* define the exact length L required in the evaluation of the integral in Eqs. (13) and (19) led us to investigate their evaluation via a Monte Carlo type simulation using the well known charged particle optics package SIMION.[6] The spectrograph layout including the HDA, 4-element lens, PSD, and gas cell was all built in the SIMION 8.1 geometry files design environment (with surface enhancement) at an accuracy of 0.254 mm per grid unit, the highest accuracy allowed by our 32 GB RAM memory computer. An example of this realization is shown in Fig. 2, where trajectory simulations for three different lifetimes τ are shown. The same electrode voltages used in the experiment were also applied to the model electrodes in order to simulate as closely as possible the experimental conditions. The numerical code was developed in the Lua programming language environment where extended use of the internally defined SIMION 8.1 functions (random number generators, cone angular distributions, etc.) was made.

In more detail, at each point of the ionic trajectory z, a number of emitted electrons is determined proportional to the product of the decay term and the solid angle term in Eq. (19) as illustrated in Fig. 4 and then multiplied by a starting indicative number N_i that determines the total number of electrons to be flown. The effects of the extended gas cell and ionic beam cylindrical shape are treated by creating electron distributions along the length of the gas cell in cylindrical disks having the radius of the ionic beam (≃0.8 mm). The electrons were emitted with the laboratory kinetic energy defined by

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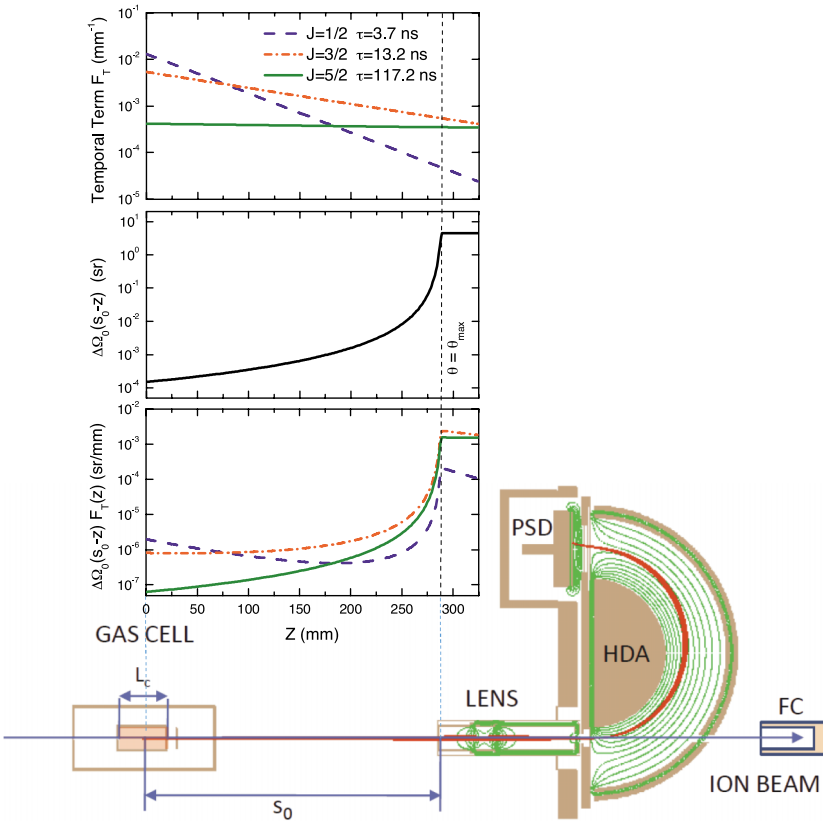

FIG. 4. z-dependence along the ion trajectory for the probability decay density $F_\tau(z) = \exp(-z/V_P\tau)/V_P\tau$ (top), the point source solid angle $\Delta\Omega_0(s_0 - z)$ (middle), and their product (bottom) as calculated for the $1s2s2p\ ^4P_J$ states in the case of a 12.0 MeV C^{4+} ionic beam (using the values of τ_J from Ref. 22—see also Table I). At the very bottom, drawn to scale is the experimental geometry showing the gas cell, the lens, and the HDA. The solid angle (computed by Eq. (22)) is seen to increase by more than four orders of magnitude, but can never surpass the maximum kinematically allowed angle θ_{max} given by Eq. (10).

Eq. (5) for the corresponding Auger energy $\varepsilon' = \varepsilon_A$, cusp energy t_p, and within a cone distribution angle θ defined either by the lens aperture of radius r at s_0 mm (see Eq. (21)) or the maximum allowed angle θ_{max} if the computed θ was found to be larger than θ_{max}. The values of ε' and t_p were obtained, respectively, from a Lorentzian and Gaussian pseudo-random distribution to describe more accurately the Auger widths and the ion beam energy width. We should emphasize here that the calculation is quite demanding in RAM memory limiting the number of electrons to be flown to a maximum of about 14×10^6 for a 32 GB RAM computer. The number of electrons created in this way was checked in our program against Eq. (19) for solid angles smaller than the maximum kinematically allowed and found to be in good agreement.

A. The role of the injection lens

As already mentioned, the number of electrons generated can increase to large numbers exceeding the available RAM memory for large consecutive solid angles. For this reason, we examined the effect of the lens on the long lived states that decay inside the region of the lens in order to limit the decaying path of the ionic beam and thus the useful number of electrons. We chose the $^4P_{5/2}$ state of C^{3+} having a relatively long lifetime of 117.2 ns[22] for the experimentally measured case of 12.0 MeV C^{4+} ionic beam. We performed the study for the lens voltages corresponding to pre-retardation factors F = 1 and F = 4. The results are presented in Fig. 5.

The results of the simulations clearly show that electrons generated inside the lens, even at the very beginning of the lens entry area, *do not make it through* and are largely filtered out before reaching the PSD area. This relatively unexpected result can be justified by a number of reasons based on the fact that the electrons generated inside the lens cannot have a solid angle larger than θ_{max}, the kinematically allowed limit. Thus, it now becomes clear that:

1. The lens focuses primarily paraxial rays into the HDA. Thus, all electrons that deviate from the paraxial rays will largely depart from the central ray neighbourhood and will either hit the walls of the lens or the walls of the entry HDA aperture and not enter the HDA. For those few electrons that accidentally make it through the HDA aperture, these will have rather large entry angles resulting in detection at the PSD, but outside the range of the ^4P peak for paraxial rays and will thus be detected as background. The situation is qualitatively illustrated in Fig. 2 (bottom).
2. The electrons that are generated at angles much larger than the paraxial values will have laboratory kinetic energies (as given by Eq. (5)) significantly different from the central energy to which the HDA and the lens have been tuned due to the kinematics presented in Sec. II. Thus, their rejection primarily by the lens is almost certain. In particular, in the case of forward emission (the + sign in Eq. (3)) considered here, it is clear that the laboratory energy $\varepsilon_+(\theta)$ will always be smaller for $\theta \neq 0$,

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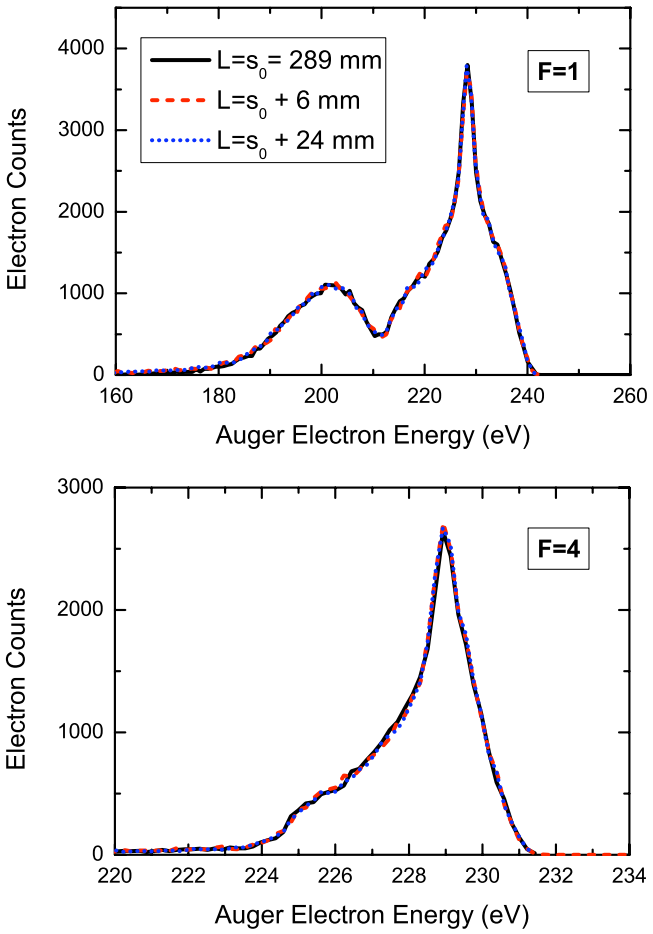

FIG. 5. The detection of the decay of the $^4P_{5/2}$ state produced by capture from the 12.0 MeV C^{4+} ionic beam for different decay termination lengths L. The value of $L = s_0$ (defined in Fig. 3) corresponds to the lens entry, while the larger values to locations inside the lens. F is the pre-retardation factor. Note the much narrower energy window of the $F = 4$ case.

and therefore, contributions from non-zero θ angles will affect mostly the low energy side of the peak clearly seen in the experimental line shape of the ^4P. This situation reverses for backward emission (the − sign in Eq. (3)) with contributions now broadening the peak on its high energy side (simulation not shown). Such backward emission for metastable Auger lines has never be reported to date and would therefore be of interest. This effect is probably also the cause of the broadening observed in the very low Auger energy prompt line shapes discussed in Ref. 23.

3. Finally, electrons generated inside the lens will also have an altered kinetic energy by the amount of the value of the lens potential at the point of generation. Therefore, their kinetic energy will be out of the acceptance energy window of the lens/HDA, and consequently, they will not be detected at all or in the worst case will be detected as a background signal on the PSD area (i.e., as in case 1).

The above three points become even stronger in the case of pre-retardation (i.e., $F > 1$), as can be clearly seen in Fig. 5, where the energy window of the lens/HDA is now significantly narrowed. The reverse is also seen to happen for $F = 1$ (see Fig. 5 top) where the larger acceptance window allows the passage of electrons contributing to the low energy hump absent in the case of $F = 4$.

We have also examined cases of very long lifetimes, like the boron $^4P_{5/2}$ state having a lifetime of 297 ns[24] for the experimentally measured case of 4 MeV B^{3+} ionic beam.[25] Such long lived states will decay along the projectile ion trajectory, not only within the lens but also within the HDA itself and beyond. This study shows that the part of the beam that decays inside the HDA only adds a background signal to the peak that can easily be subtracted without affecting the results.

In conclusion, the lens is found to act as an efficient filter rejecting electrons emitted outside the lens with large solid angles that substantially deviate from the paraxial values as well as those generated inside the lens itself. Its particular filtering action cannot be readily assessed theoretically. Here, it is simulated by SIMION showing that for our particular experimental setup, the end point L could be safely set to 6 mm inside the lens for all metastable state lifetimes considered.

V. RESULTS AND DISCUSSION

We applied our simulations, described in Sec. IV, to one of our previously published[13] spectra that from 25.3 MeV F^{7+} + H_2, as well as to new spectra from 12.0 MeV C^{4+} + Ne collisions obtained for the APAPES project[11] where the ^4P_J states have even longer lifetimes. In order to obtain the solid angle correction factor G_τ in simulation, we worked as follows. The correction factor G_{τ_J} was determined for the SIMION distance s_0 (see Fig. 3) as the ratio of the number of PSD recorded electrons from the metastable state J under the peak of interest to that of the same but assuming a prompt decay which is equivalent to evaluating the ratio in Eq. (16) for each J. It should be noted that we have not considered any possible effects arising from non-isotropic angular distributions as these are expected to be minimal for the case of the $1s2s2p\,^4P/^2P$ ratio (the quartet and doublet P states can be expected to have very similar angular distributions) of particular interest to our work. In Table I, the Auger lifetimes τ_J and Auger yields ξ_J for the examined cases are listed along with other parameters soon to be explained.

Following the above procedure, we primarily obtained the electron yields for the ^4P_J state as well as the corresponding *reference* prompt state, i.e., the state with the same energy as the ^4P_J state but that decays promptly entirely inside the gas cell, for the aforementioned collisional systems. Then, the J-averaged correction factors G_τ were determined according to Eq. (15). The calculations were performed using two different sets of theoretical Auger lifetimes and yields that exist in the literature for both ions.[22,24,26,27] The resulting line profiles were normalized to the existing experimental data and are presented in Fig. 6 for comparison. Only the set of theoretical Auger lifetimes and yields of Refs. 24 and 26 is included in Fig. 6, as it turned out that no essential differences were noticeable between spectra of either set. It is clearly evident that our Monte Carlo calculations reproduce with remarkable accuracy the line shapes of both the metastable ^4P and the prompt states for both collision systems.

Regarding the prompt states, although not of direct interest in this work, we chose to include them as a further

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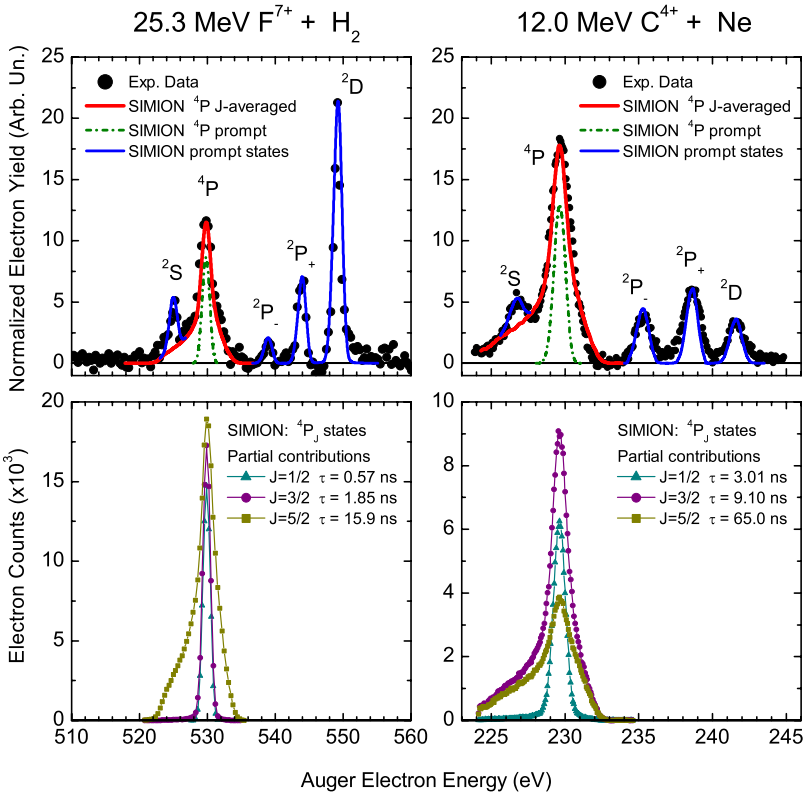

FIG. 6. [Top] Presentation of SIMION Monte Carlo type calculations of the line shape of the Auger electron yields from metastable and prompt states in comparison to experimental data obtained in collisions of 25.3 MeV $F^{7+}+H_2$ (left—Ref. 13) and of 12.0 MeV $C^{4+}+Ne$ (right) taken with $F=4$. SIMION calculations are normalized to the experimental electron yields. The blue lines correspond to the prompt states. The green dashed-dotted lines correspond to a "reference" prompt line with the energy of the ^4P state, i.e., a ^4P state that decays entirely inside the gas cell. The red line corresponds to the J-averaged ^4P_J states. [Bottom] Individual contributions of the J states to the ^4P state. The Auger lifetimes and yields used were taken from Refs. 24 and 26.

test of our simulation procedure. Thus, we tried to reproduce the shape and FWHM of the prompt states including, aside from the earlier presented geometric and kinematic terms, the natural widths of the Auger states found from the literature. However, we were able to accurately reproduce the experimental line shapes only after also taking into account the small uncertainty in the ion beam energy. This is of the same order as the kinematic broadening or even larger[1] and is often overlooked. As can be seen in Fig. 6, the experimental energy resolution is different for each of the examined cases. This is largely due to the different beam energy widths of ~0.13% for the fluorine beam of the 7 MV tandem Van-de-Graaff accelerator at the J. R. Macdonald Laboratory at Kansas State University and of ~0.21% for the carbon beam of the 5 MV NCSR Demokritos tandem Van-de-Graaff accelerator. Thus, the observed good agreement also seen for prompt states further reinforces our confidence in these calculations.

In more detail, in the fluorine case, it is apparent that the $J=1/2$ and $J=3/2$ states behave essentially as prompt states due to their relatively short lifetimes. Therefore, they do not contribute to the low energy shoulder of the ^4P peak which is entirely due to the $J=5/2$ state. The relatively long lifetime of the $J=5/2$ state results in a considerable amount of decay close to and inside the lens. Thus, angles largely departing from zero degrees (emission in the forward direction) *always* bring about *smaller* kinetic energies according to Eq. (3) (+ case) that do not meet the optimum focusing conditions and therefore result in the observed *low energy* shoulder. Alternatively, for emission in the backward direction, this condition should be reversed resulting in a shoulder only on the *high energy* side. A small disagreement in the shape of the prompt ^2D peak is due to its known Fano line shape that has not been included in our simulation. In addition, a "reference" prompt ^4P peak is also presented along with the J-averaged ^4P peak serving as a qualitative measure of the solid angle correction factor G_τ under investigation.

The quantitative determination of the J-averaged correction factors G_τ for both theoretical sets of Auger lifetimes and yields is presented in Table I. We note that despite the fact that the two theoretical calculations differ considerably in the values of τ and ξ for the $J=3/2$ state, the correction factors G_τ are similar and the line shapes of the ^4P peaks are practically identical. This is due to the rather small Auger yields of the $J=3/2$ state compared to those for the $J=1/2$ and $J=5/2$ states that are close to unity resulting in the significantly reduced overall contribution of the $J=3/2$ state to the J-averaged ^4P line shapes and correction factors G_τ.

For the case of carbon, only the $J=1/2$ state behaves as a prompt state, while both long lived $J=3/2$ and $J=5/2$ contribute to the low energy shoulder of the ^4P peak. The shape of the ^4P peak is again reproduced with remarkable accuracy as well as the line shape of the prompt states for which agreement with the experiment is considerably improved by the inclusion of the aforementioned beam energy width. The quite different values obtained for the J-averaged correction factors G_τ clearly reflect the factor of 2 difference in the

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calculated lifetimes of the $J = 5/2$ state found in the literature (it is reminded, however, that the lifetime from Ref. 24 was estimated by extrapolation). Despite this difference, the shape of the ^4P peak is not particularly affected, even though its area has been adjusted accordingly.

Clearly, there is a need for accurate theoretical calculations of Auger lifetimes and yields for first row ions to aid the reliable determination of the J-averaged correction factors G_τ to be used in the APAPES program.

VI. SUMMARY AND CONCLUSION

In this report, we have shown how a Monte Carlo type approach can be combined with SIMION to accurately simulate a high resolution *projectile* Auger electron spectrum recorded by a hemispherical spectrograph with injection lens and 2D position sensitive detector. In particular, we show that Auger electron line shapes can be well characterized even in the case of electrons emitted from *long lived* (metastable) states of fast moving ions observed in the beam direction. Such a well-known example is provided by the $1s2s2p\,^4P$ metastable state of first row ions formed in MeV collisions with atoms having a lifetime in the tens of ns. Our approach extends older similar treatments applied to two-stage parallel plate slit spectrometers to also include possible contributions from Auger decays inside the lens and/or hemispherical analyzer itself. In addition, kinematic effects particular to Auger emission from fast moving projectile ions such as line broadening and solid angle limitations are included here for the first time allowing for a more accurate line shape modeling. Our SIMION simulations were compared to experiment and found to be in excellent agreement with previously recorded $1s2s2p\,^4P$ Auger line shape measurements in 25.3 MeV $F^{7+} + H_2$, as well as with new experimental data from collisions of 12.0 MeV $C^{4+} + Ne$ provided by our new experimental setup. For the first time, the $1s2s2p\,^4P_J$ Auger line shape, and in particular its prominent low energy shoulder, is explained in terms of the differential metastability of its J-components leading to different kinematic broadenings caused by the much larger electron emission angles that occur for decays close to the spectrometer. These results will be particularly useful in the accurate modeling of the metastable $1s2s2p\,^4P$ and prompt $1s2s2p\,^2P$ Auger yields of first row ions and the determination of their ratio, recently of special interest due to its unexpected non-statistical nature.

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Voltage optimization of a 4-element injection lens on a hemispherical spectrograph with virtual entry aperture

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ABSTRACT

We present simulation results for a biased paracentric hemispherical deflector analyzer equipped with a 4-element input lens and a position sensitive detector used in our zero-degree Auger projectile spectroscopy apparatus. Calculations of electron trajectories traversing the lens and analyzer fields were performed and cross checked using both boundary-element and finite-difference methods. The two middle lens electrode voltages were varied as free parameters, while various criteria were used to select their optimal values in an effort to obtain improved energy resolution.

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1. Introduction

Accelerator-based atomic physics can now be investigated in Greece through the APAPES project [1] experimental setup with a newly operational innovative electron spectroscopy apparatus [2] composed of a paracentric hemispherical deflector analyzer (HDA) [3–7] equipped with a 4-element injection lens and a 2-D position sensitive detector (PSD) to be used for zero-degree Auger projectile spectroscopy (ZAPS) of ion–atom collisions [6,8,9].

In order to improve our experimental techniques on recording Auger electron energy spectra we also searched in *simulation* for the optimal lens voltages that would allow us to reach the highest energy resolution in our ZAPS [7,8] experimental setup. In this ZAPS apparatus, the electrons are measured in the direction of the beam (zero degrees) and therefore the physical size of the HDA entry aperture must be large (6 mm) to allow the uninhibited passage of the *ion beam* itself, which goes straight through the lens and HDA exiting from a hole in the back of the HDA and eventually stopped in a faraday cup used for ion beam normalization. Thus, the lens system plays a particularly important role in regulating the electron energy resolution of the analyzer since it defines the size of the much smaller *virtual* HDA entry aperture [10], which goes into the energy resolution formula. The values of the lens voltage combination, V_{L4} and V_{L5}, (see Fig. 1) and their relation to the size of the beam spot on the PSD, form families of elliptical-like contours [11], and have been investigated for different pre-retardation factors, $F = E_{s0}/E_0$, where E_{s0} is the electron source energy and E_0, is the pass energy ($F = 1$ for no pre-retardation, and $F > 1$ when $E_s < E_{s0}$). The relation between beam spot size and energy resolution was evaluated by means of computer simulations of electron trajectories flying through the entire spectrometer including the injection lens system.

The lens optimization was carried out by simulations using the SIMION 8.1 charge particle optics software package [12]. SIMION solved the Laplace equation in the lens and the HDA for the simulated experimental setup utilizing the finite difference method. Simple initial electron distributions were flown through the lens, HDA and all the way through to the PSD. The two lens voltages V_{L4} and V_{L5} were varied as free parameters while various criteria were used to select the optimal voltage combinations including PSD beam spot size minimization, lens magnification and beam angle minimization at the lens image plane and others in an effort to obtain improved energy resolution. The size of the resulting beam spot along the dispersion direction at the PSD, x_{span} was recorded for each electron distribution. The simulations were carried out for various

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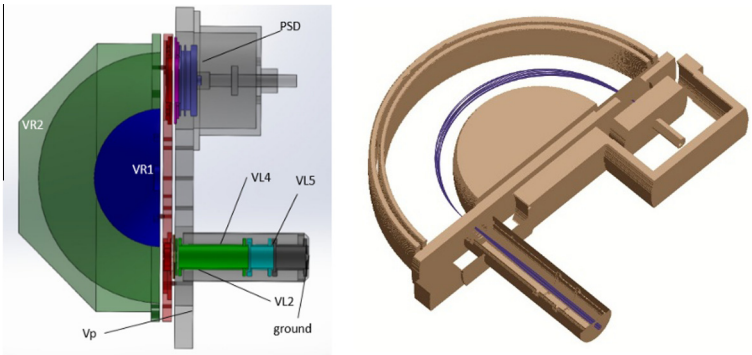

Fig. 1. (Left) Schematic representation of the spectrograph consisting of an injection lens, the HDA and the PSD. All the important electrode elements are shown. Each color represents a different voltage. V_{L4} and V_{L5} are the voltages on the corresponding lens electrodes varied in the simulations. The plate voltage V_p is responsible for the final electron deceleration. (Right) SIMION 3-D cropped image showing electron trajectories in the lens and HDA. Electron trajectories are started at the target ion–atom collision region about 288 mm away (not shown). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1
List of simulation parameters for minimum x_{span} values obtained in SIMION for $F = 1$, 4 and 8. Also included are corresponding values of the beam width, y_{span} in the non-dispersive direction (y-axis) and the positions of the focal (z_f) and image (z_i) planes with the corresponding linear magnification M_L. The lens entry marks the position of $z = 0$.

F	V_{L4} (V)	V_{L5} (V)	SIMION determined quantities				
			x_{span} (mm)	y_{span} (mm)	z_f (mm)	z_i (mm)	$\|M_L\|$
1	−570	550	0.443	0.456	−143.8	−163.3	0.245
4	−570	625	0.679	0.738	−138.1	−160.0	0.387
8	−840	−510	0.904	0.999	−133.2	−157.9	0.512

lens pre-retardation factors F. The validity of the SIMION results were finally cross-checked with the boundary-element method (BEM) [13] and good agreement was invariably found.

The lens voltages obtained from simulations in this way will be soon tested on the actual experimental apparatus with the expectation that they will provide further improved energy resolution compared to the previously empirically found lens voltages [7].

2. Experimental setup

The APAPES experimental station is at the 5 MV 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. The description of the new beam line has been given elsewhere [2]. In Fig. 1 (left), assembly drawings of the HDA including 4-element injection lens and PSD in SolidWorks 3D [14] were used to prepare accurate geometry input data for the SIMION program using so called "geometry" files. Fig. 1

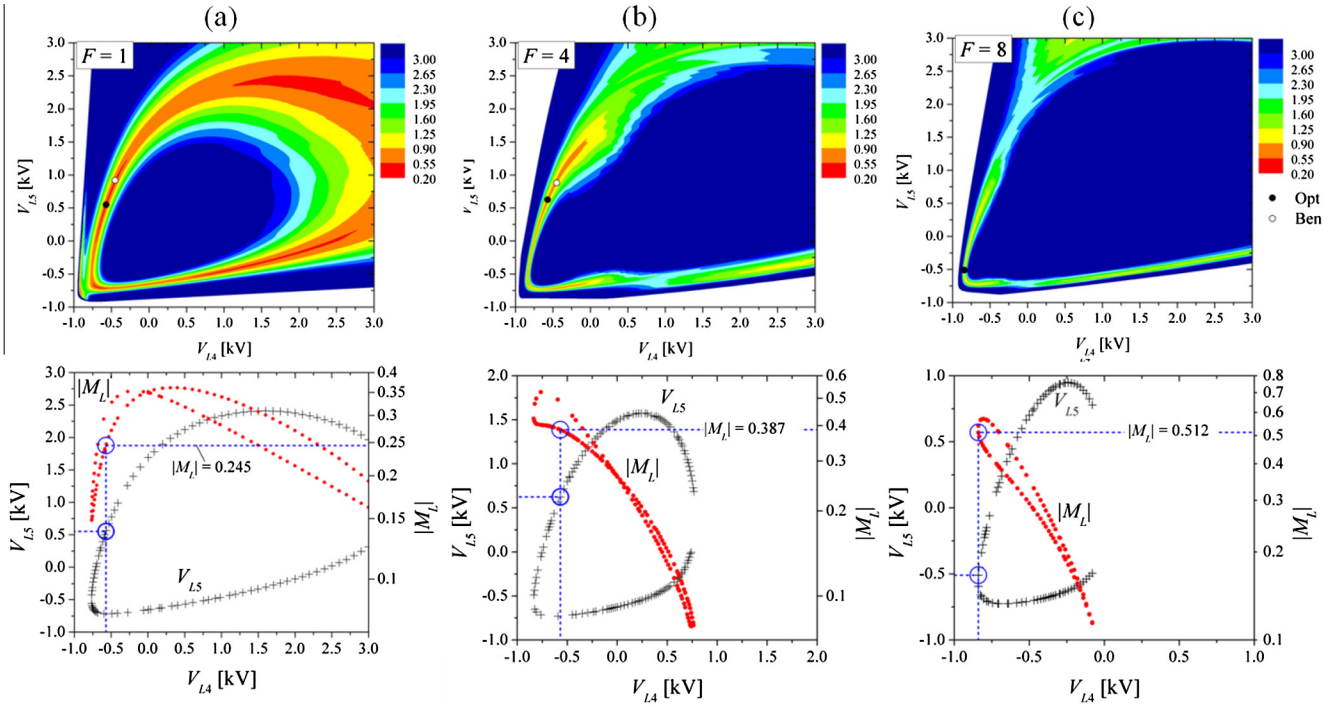

Fig. 2. Simulation results for (a) $F = 1$, (b) $F = 4$ and (c) $F = 8$. (Top) 2-D contour plots of the beam trace width x_{span} (in mm) as functions of V_{L4} and V_{L4} lens voltages. The optimal values of V_{L4} and V_{L5} are listed in Table 1 and shown as black dots, while older empirically found values are shown as white dots. (Bottom) Lens voltages V_{L4} and V_{L5} interdependence illustrated for the zoom-lens mode is plotted as black crosses. The corresponding linear magnification $|M_L|$ (refer to the logarithmic scale to the right) with respect to V_{L4} is also plotted as red dots. The open blue circles show the optimal working points (V_{L4}, V_{L5}, $|M_L|$) listed in Table 1. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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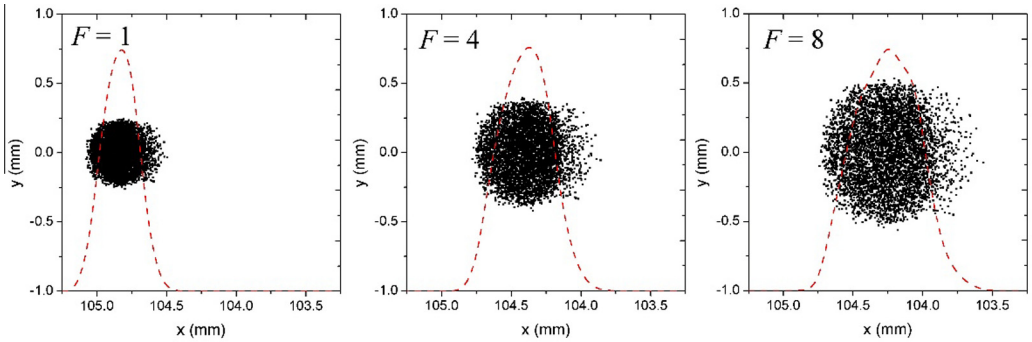

Fig. 3. Calculated spot size on the detector plane (*xy*-plane) of the PSD at the exit of the HDA for $F = 1$, 4 and 8. Normalized line profiles resulting from the vertical projections of the electron distributions along the dispersion direction (*x*-axis) are also shown from which the value of the FWHM could be determined.

(right) shows an example of simulated trajectories in the analyzer system for 1 keV pass energy and $F = 1$.

3. Simulation results

The geometry files used for the simulations in SIMION 8.1 utilized surface enhancement with a grid unit (gu) density of 0.254 mm/gu to ensure the highest accuracy conditions for the simulated apparatus. Electrode voltages for each of the four elements of the injection lens and the HDA itself as well as the initial conditions of the electron beam were controlled independently in SIMION by the use of Lua programming. The entire voltage space of both V_{L4} and V_{L5} lens voltages was scanned in steps of $\Delta V = 5$ V, while x_{span} was recorded for each combination. In our simulation, minimum values of x_{span} were found to be related to HDA optimal energy resolution as also expected from basic theory.

Simulations results are plotted in Fig. 2 (top) as 2-D contours of x_{span} versus V_{L4} and V_{L5} for $E_{s0} = 1$ keV and $F = 1$, 4 and 8. The optimal V_{L4} and V_{L5} voltage sets are displayed as black dots, while empirically discovered lens voltages using Auger lines produced in ion–atom collisions and previously used are also displayed as white dots and seen to also lie along the same contours. In Fig. 2 (bottom), we display the relationship between V_{L4} and V_{L5} and the variation of the linear magnification $|M_L|$ with V_{L4}, when the object z_0 and image z_i plane positions are held fixed (typically referred to as *zoom-lens curves*) [15].

In all cases the object plane position was set at $z_0 = +288.47$ mm while the image plane position is $z_i = -163.3$ mm for $F = 1$, $z_i = -160.0$ mm for $F = 4$ and $z_i = -157.9$ mm for $F = 8$, respectively. The lens entry is at $z = 0$, with the z-axis decreasing in the direction of the electron path. The lens itself has a total length of 149 mm. The detector is placed at a distance h = 17.56 mm from the HDA exit plane. The linear magnification at the optimal working points is also shown in red in Fig. 2 (bottom) and listed in Table 1.

In Table 1 we list the combinations of V_{L4} and V_{L5} voltages for $F = 1$, 4 and 8 that gave the minimum beam trace widths x_{span} together with the values of other important lens parameters.

In Fig. 3, the calculated exit spot sizes are shown on the detector plane (*xy*-plane) for each of the F values listed in Table 1. The size of the spot is seen to increase with F as the lens linear magnification also increases in agreement with the Helmholtz–Lagrange law that sets the ultimate limits on the energy resolution [10].

4. Summary and conclusions

Electron trajectories were simulated in the biased paracentric HDA [with 4-element injection lens and 2-dimensional position sensitive detector (PSD)] modeling existing apparatus. Optimal lens voltages were found by minimizing the measured simulated beam widths on the PSD plane leading to optimal energy resolution. We expect this approach to be helpful to experimenters in determining the lens voltages for best energy resolution, which can be done in simulation with substantial savings in overall effort. In addition, once such a simulation has been setup and tested, it can also be used beneficially by students as a learning tool to increase understanding of the experimental apparatus under optimal resolution conditions.

Acknowledgements

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Β΄.2 Συμμετοχές σε διεθνή συνέδρια

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Atomic Physics with Accelerators: Projectile Electron Spectroscopy (APAPES)*

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Abstract. The new research initiative APAPES (http://apapes.physics.uoc.gr/) has already established a new experimental station with a beam line dedicated for atomic collisions physics research, at the 5 MV TANDEM accelerator of the National Research Centre "Demokritos" in Athens, Greece. A complete zero-degree Auger projectile spectroscopy (ZAPS) apparatus has been put together to perform high resolution studies of electrons emitted in ion-atom collisions. A single stage hemispherical spectrometer with a 2-dimensional Position Sensitive Detector (PSD) combined with a doubly-differentially pumped gas target will be used to perform a systematic isoelectronic investigation of K-Auger spectra emitted from collisions of pre-excited and ground state He-like ions with gas targets using novel techniques. Our intention is to provide a more thorough understanding of cascade feeding of the 1s2s2p ^{4}P metastable states produced by electron capture in collisions of He-like ions with gas targets and further elucidate their role in the non-statistical production of excited three-electron 1s2s2p states by electron capture, recently a field of conflicting interpretations awaiting further resolution. At the moment, the apparatus is being completed and the spectrometer will soon be fully operational. Here we present the project progress and the recent high resolution spectrum obtained in collisions of 12 MeV C^{4+} on a Neon gas target.

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1. Introduction

The APAPES initiative establishes in Greece the discipline of Atomic Physics with Accelerators, a field with important contributions to fusion, hot plasmas, astrophysics, accelerator technology and basic atomic physics of ion-atom collision dynamics, structure and technology. This is being accomplished by combining the existing interdisciplinary atomic collisions expertise from three Greek universities, the strong support of distinguished foreign researchers and the high technical ion-beam know-how of the Demokritos Tandem accelerator group into a cohesive initiative.

2. Experimental setup

The new experimental setup includes a single stage hemispherical spectrometer with injection lens and 2-dimensional PSD combined with a doubly-differentially pumped gas target. It has been used in previous work at Kansas State Univ. [1], but recently moved to the Athens Tandem. This high-efficiency, high-resolution ZAPS system is ideally suited for use in the electron spectroscopy of weak ion beams such as the ones called for in this work and due to its PSD is also about 15-20 times more efficient than conventional single channel devices (e.g. two-stage parallel plate electron spectrometers [2]). Additionally, the paracentric entry of the Hemispherical Deflector Analyser (HDA) [3] is a novel feature adding further high resolution capability not available to conventional centric HDAs [4, 5]. In the two following pictures we give a general presentation of the experimental setup. In figure 1 a panoramic view of the beam line is shown and in figure 2 the doubly differentially pumped target gas cell, the HDA, the 4-element input lens and the PSD are shown inside the vacuum chamber.

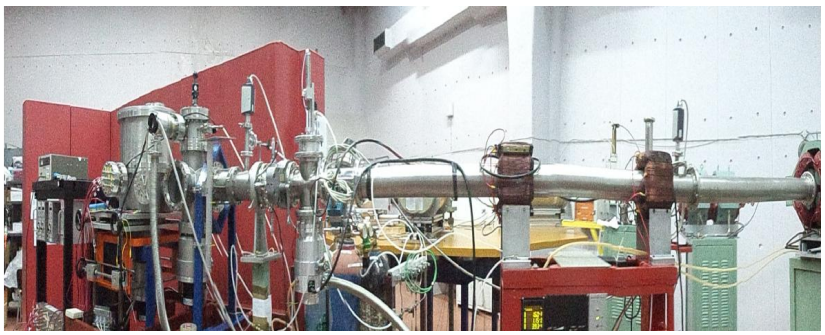

Figure 1. Panoramic view of the new beam line at the 5 MV Demokritos Tandem.

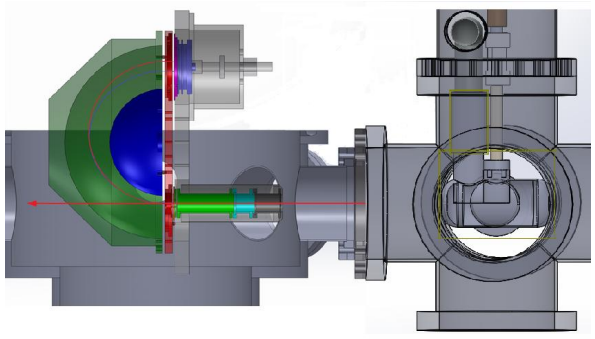

Figure 2. From right to left: The doubly-differentially pumped target gas cell, the 4-element input lens, the HDA and the 2-D PSD. Each colour denotes a different voltage.

3. Electron capture

The various 1s2s2*l* lines observed in the Auger spectra result from the capture of a target electron to one of the possible (1*s*2s2*l*) states. With the use of the well known COWAN Hartree-Fock package [6] the relevant F^{6+}(1s2s*nl* $^{2,4}L_J$) Li-like energy levels, including dipole and Auger transition rates for principal quantum numbers $2 \le n \le 5$ and $l=0$, n-1 were calculated [7]. In figure 3 the energy level scheme along with the corresponding transition rates is shown. Basic quantum mechanics requires the spin coupling of a 2p electron to the 1s2s ^{3}S state yielding 1s2s2p ^{4}P quartet and 1s2s2p ^{2}P doublet states to be in the ratio of 2:1, i.e. $R=\sigma(1s2s2p\ ^4P)/\sigma(1s2s2p\ ^2P) = 2$. However, it has been documented in the literature that the values of R extracted from the spectra are much larger having values of R~6-9 [7-10]. Our intention is to provide a more thorough understanding of cascade feeding of the 1s2s2p ^{4}P metastable states produced by electron capture in collisions of He-like ions with gas targets and further elucidate their role in the non-statistical production of excited three-electron 1s2s2p states by electron capture, recently a field of conflicting interpretations awaiting further resolution.

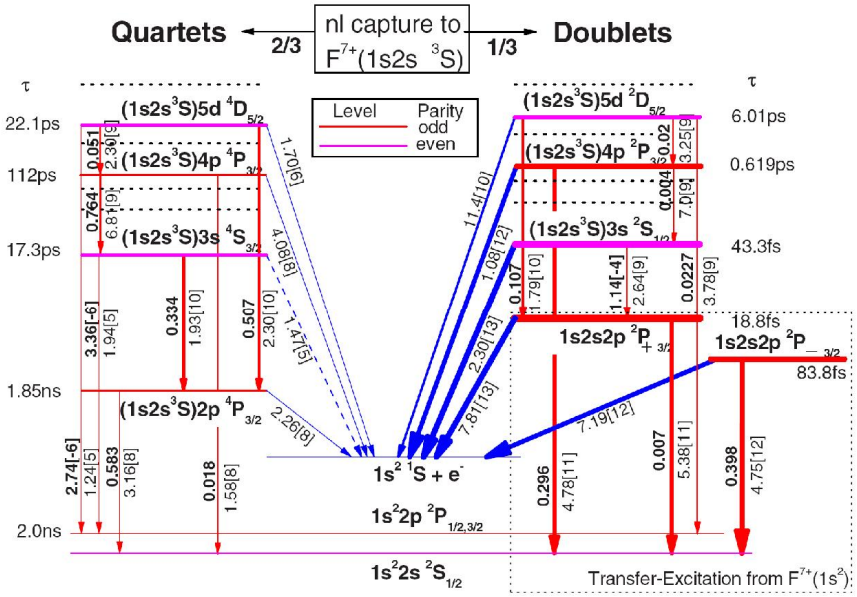

Figure 3. Li-like quartet and doublet F^{6+} 1s2s*nl* energy level scheme (not to scale) resulting from single electron *nl* capture to F^{7+} 1s2s ^{3}S. Only a few representative levels are indicated for clarity. Arrows represent transitions with widths roughly proportional to their strength radiative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

4. Electron Energy spectrum

Our first high resolution Auger spectrum was obtained recently with our new setup using the 5 MV tandem Van der Graf accelerator and is shown in figure 4. A 12 MeV C^{4+} beam was collimated and directed into the doubly-differentially pumped gas cell that contains gaseous neon target. The gas cell pressure during the measurement was 20 mTorr. The tuning energy W of the analyzer was set at 1525 eV. High resolution was achieved by retarding the electrons using a deceleration factor of F=4. Analysed electrons were counted and normalized to the incident beam current, which was collected at the Faraday cup. The similarity with previous published works is obvious [9].

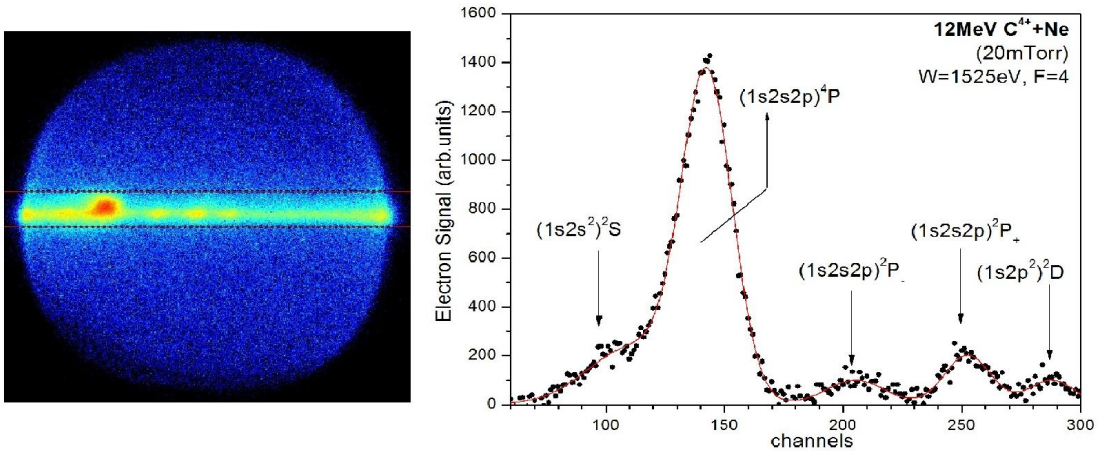

Figure 4. (a) 2-D PSD Image, (b) Projection of the PSD image within the selected region shown in (a). The ^{4}P line is seen to be broadened. Its considerable longer life time makes it decays closer to the spectrometer with increased angular acceptance and therefore kinematic broadening.

5. Future developments

Future developments on the beam line include the upgrade of the Tandem accelerator to also include a recirculating gas stripper in the accelerator terminal, along with a post-stripping stage, for both gas and foil stripping. These, along with the placement of a number of beam profile monitors will allow for better control of the beam both as to its transmission as well as to its composition of the excited states.

6. Acknowledgements

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Use of Gas and Foil strippers for the production of He-like ionic beams in both pure ground state ($1s^2$) and mixed states ($1s^2$, 1s2s) for zero-degree Auger Projectile Electron Spectroscopy

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Synopsis We present the unique benefits of gas and foil pre- and post- stripping in the production of pure ground state ($1s^2$), as well as mixed ($1s^2$, 1s2s) state He-like beams. The availability of such beams in TANDEM accelerators is of vital importance in studies concerning the population mechanisms of the 1s2s2p ^{4}P metastable states produced in collisions of these He-like beams with gaseous targets.

The new research initiative APAPES funded by THALES* has so far established a new experimental station at the 5.5MV TANDEM of the NCSR "Demokritos" in Athens with a dedicated beamline for atomic collisions physics research [1].

The main apparatus, developed for zero-degree Auger projectile spectroscopy, has been put together to perform high resolution studies of electrons emitted at zero degrees with respect to the ionic beam in ion-atom collisions. This apparatus consists of a hemispherical deflector analyser equipped with a 4-element entry zoom lens and a 2-dimensional position sensitive detector in operation with a doubly-differentially pumped gas target. It is currently fully operational and used in performing systematic isoelectronic investigations of K-Auger spectra emitted from collisions of He-like ions with gas targets. Our goal is to provide a better understanding of the cascade feeding of the 1s2s2p ^{4}P metastable states produced in collisions of He-like and H-like ions with gaseous targets [2].

Our experimental results so far were limited to the case of capture measurements to a mixed state ($1s^2$, $1s2s\,^3S$) of 12 MeV C^{4+} ion beam generated at the TANDEM terminal foil stripper. In order to perform measurements with pure as well as mixed state beams, it is necessary to incorporate: i) A gas stripper hosted inside the TANDEM terminal that will allow us to obtain pure ground state ionic beams [3], ii) A stripping point along the beam line of the accelerator hosting both foil and gas post strippers. This will allow us to obtain mixed state beams at different fractions vital for our research goals. Both options are under construction and should soon be fully operational.

The expected charge state intensities resulting from the stripping are calculated from a charge state analysis code using mainly the semi-empirical formulas of Nikolaev Dimitriev [4] and Sayer [5] along with the energy of the beam, its characteristics (Z, atomic mass) and incoming charge state.

Measurements of zero-degree Auger spectra following single state electron transfer to mixed state C^{4+} ($1s^2$, $1s2s\,^3S$) in collisions with various gaseous targets along with a thorough description of both gas and carbon foil strippers will be presented.

*Co-financed by the European Union and Greek national funds through OP: Education and Lifelong Learning, Research Program: THALES.

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Separation and solid angle correction of the metastable 1s2s2p ^{4}P Auger yield produced in ion-atom collisions using the biased gas cell technique: A tool for the determination of the population mechanisms

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Synopsis: We demonstrate an experimental approach to the solid angle correction needed for the metastable 1s2s2p ^{4}P state obtained in ion-atom collisions with gaseous targets. By applying a small bias voltage V_{GC} on the target gas cell, the ^{4}P contributions are separated into two peaks one arising from inside (which is shifted by e V_{GC}) and the other outside the gas cell which is unshifted. Using SIMION we compute the correction in each case and perform a consistency check on our approach.

A persisting problem in the analysis of Auger spectra obtained in collisions of He-like ions with gaseous targets using zero-degree Auger projectile spectroscopy is the determination of the correct contributions from the 1s2s2p $^4P_{1/2,3/2,5/2}$ metastable states to the measured total ^{4}P Auger electron yield. Their inherent long lifetime (>10^{-9}s) results in their decay all along the projectile path towards (and through) the spectrometer. Thus, the overall electron detection solid angle varies with the position of electron emission and therefore a considerable correction to the ^4P_J electron yields is needed. In the literature this correction has been treated either geometrically [1] or by SIMION simulations [2].

Another existing approach, which however has not been given sufficient attention, is adopted here. The separation of the ^4P_J yields produced inside and outside the target can be accomplished experimentally by applying a relatively small voltage (e.g. -20 Volts) to the gas cell [3]. Thus, the ^{4}P line now breaks in the spectrum into two separate components, i.e. one produced inside and the one produced outside the gas cell. The one produced inside the gas cell can be straightforwardly used with minimal correction in the determination of the ratio R=^{4}P/^{2}P of production cross sections. This ratio, has been of recent interest as large departures from the expected statistical value of R=2 have been reported lending themselves to various explanations as to the possible mechanisms involved [4-5].

Here we present results of the application of this method in collisions of 12 MeV C^{4+} with gaseous targets (H_2, He, N_2, Ne). The ratio R is then estimated, details of which will be provided. These results are part of the APAPES research initiative [6].

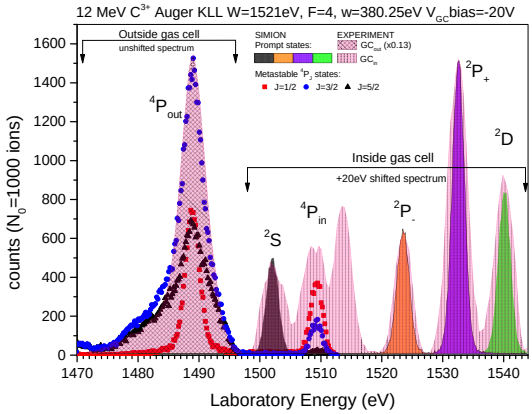

Figure 1. Comparison of SIMION simulations to experimental spectra. In both cases, the ^{4}P line is seen to be broken into two separate components, the unshifted line from electrons emitted outside the gas cell and the shifted line from electrons produced from inside the gas cell which is biased at V_{GC} = -20V. SIMION results (scaled to the experimental spectrum) are seen to nicely reproduce the line shapes of both the metastable ^{4}P state and the prompt doublet states.

*Co-financed by the European Union and Greek national funds through OP: Education and Lifelong Learning, Research Program: THALES.

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Optimal operation of a 4-element injection lens in a hemispherical spectrograph: FDM/BEM simulation and experimental demonstration

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Synopsis We have investigated the voltage settings for the 4-element injection lens of a biased paracentric hemispherical deflection analyzer (HDA) with virtual entry aperture using numerical methods. The two lens electrode voltages were varied as free parameters while the electron optical properties of the analyzer were calculated from trajectories with test initial distributions for different pre-retardation factors in an effort to obtain improved energy resolution. The resulting lens voltages were then also tested on the existing HDA spectrometer at the Tandem Accelerator Laboratory, while simulated and measured line profile characteristics were compared, particularly at the best resolution working points.

The biased paracentric hemispherical deflection analyzers represent a novel class of HDAs, which use the lensing action of the strong fringing fields at its entry, to restore the first order focus characteristics of ideal HDAs in a controlled way [1,2]. Here, we extend previous investigations to the study of the electron optical properties of such an HDA as a function of lens voltages, and compare our results to experimental measurements taken with the HDA at the Tandem Accelerator Laboratory [3].

Figure 1(a) shows the schematic of the biased paracentric HDA equipped with a 4-element injection lens and position sensitive detector (PSD). The lens system plays a particularly important role in regulating the energy resolution of the analyzer since it defines the size of the virtual entry aperture. The two lens voltage combinations, V_{L4} and V_{L5}, were found to belong to the families of elliptical-like contours, as shown in Figure 1(b), and were investigated for different pre-retardation factors, $F = E_{s0}/qV_p$, where E_{s0} is the electron source energy, and V_p is the HDA plate voltage (F = 1 for no pre-retardation). The correlation between F and the energy resolution was evaluated by means of both experimental measurements and computer simulations of the entire trajectories including the injection lens system. Two numerical methods, the finite difference method (FDM) and boundary element method (BEM) [4], were employed in the solution of the electrostatic problem.

All four combinations of positive and negative voltages gave rise to energy resolution minima from which only the subset with the most practical values were further investigated in more detail.

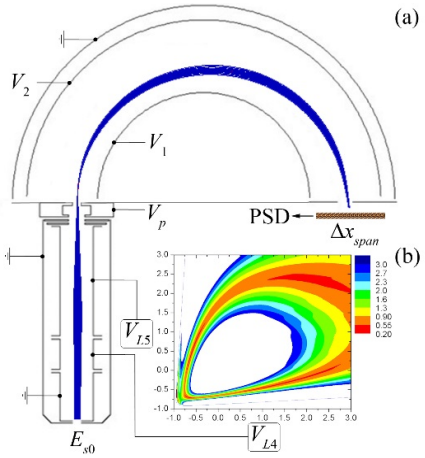

Figure 1. (a) Schematic view of the complete analyzer system. (b) 2-D contour map of the beam trace width Δx_{span} versus V_{L4} and V_{L5} (in kV) for F = 1.

This research has been co-financed by the European Union and Greek national funds through OP: Education and Lifelong Learning, Research Program: THALES.

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Investigation of the dependence of the energy resolution of a hemispherical deflection analyzer on the distance of the position sensitive detector from the focal plane

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Synopsis We investigate the energy resolution and line shape of a biased paracentric hemispherical deflector analyzer considering the distance between the exit focal plane and the detection plane. Equipped with a piezo-electrically controlled location of a 2D position sensitive detector we were able to accurately determine the optimum conditions for best energy resolution. The voltages of the injection lens of the spectrometer were also optimized for each location.

Most modern hemispherical deflector analyzers (HDAs) are equipped with an electrostatic injection zoom lens and a position sensitive detector (PSD). Practical geometrical constraints (fringing field correctors, grids, their mountings etc.) does not always allow the PSD placement at the optimal position, i.e. the first-order focal plane following 180° deflection. Page and Read [1] have shown in simulations that an optimal choice on the distance *h* between the focal plane and the detection plane might exist for which non-linearities in the energy of the electrons across the PSD become minimized.

Here, we present a study on the *h* dependence of the energy resolution and line shape in a biased paracentric HDA. The HDA is equipped with a 4-element entry zoom lens and a 2-dimensional PSD in operation with a doubly-differentially pumped gas target. It is a part of the experimental station at the 5.5MV TANDEM of the NCSR "Demokritos" in Athens developed in the new research initiative APAPES [2] funded by THALES. The setup is primarily dedicated to zero-degree Auger projectile spectroscopy, performing high resolution studies of electrons emitted in ion-atom collisions.

Recently, a piezo-electric motor on the shaft on which the PSD is supported has been installed (see Figure 1). This allows us to electronically control the distance *h* of the PSD with respect to the HDA exit focal plane thus enabling an experimental study of its effect on the measured line shape. Moreover, at different values of the distance *h* of the PSD, the injection lens voltages are optimized appropriately including this vital parameter in the study as well [3]. Cold cathode electron gun beams are mostly utilized while electrons resulting from ion-atom collisions at zero-degrees with respect to the ionic beam are complementing the study. In order to understand in detail our findings we also included simulations utilizing the SIMION 8.1 ion optics simulation package.

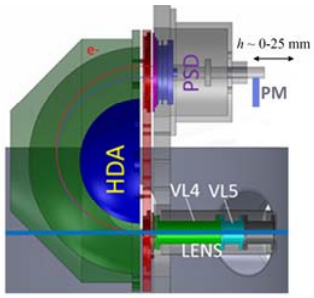

Figure 1. Schematic view of an HDA spectrometer. The PSD is placed a distance *h* from the focusing plane of the HDA.

This research has been co-financed by the European Union and Greek national funds through OP: Education and Lifelong Learning, Research Program: THALES.

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High Resolution Auger Projectile Electron Spectroscopy of Li-like Ions Produced by Electron Capture in collision of He-like ions with Gaseous targets

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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 spectrometer 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 and phrases: electron capture, ion-atom collisions, zero-degree Auger projectile spectroscopy, three-electron spin statistics, K-Auger spectra

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I 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 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.

II 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 Fig. 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.

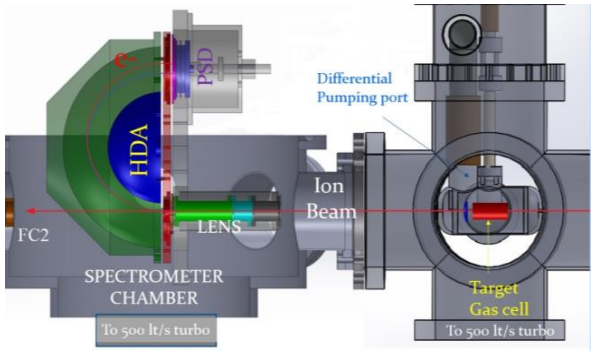

Figure 1: From right to left: Double differentially pumped target gas cell, 4-element injection lens, paracentric HDA with 2-D PSD and final Faraday Cup (FC2). The length of the target gas cell was L_c= 49.9 mm and the distance of its center to the lens entry s_0=288.5 mm

III 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 Fig. 2. As is evident, the *doublets* (Fig. 2, right) Auger decay strongly to the K-shell, while the *quartets* (Fig. 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 ^{3}S state yielding 1s2s2p ^{4}P quartet and 1s2s2p ^{2}P 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~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 ^{4}P 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 ^{4}P 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 ^{4}P state production, without, however, any supporting theoretical calculation [16], to date.

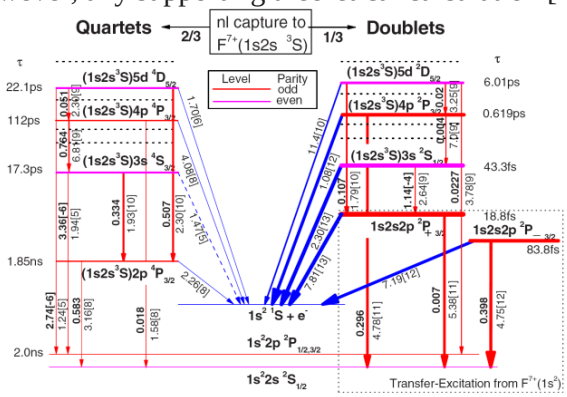

Figure 2: Li-like quartet and doublet F^{6+} 1s2s*nl* energy level scheme (not to scale) resulting from single electron *nl* capture to F^{7+} 1s2s ^{3}S states. Only a few representative levels are indicated. Arrows represent transitions with widths roughly proportional to their strength: radiative 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]).

Finally, it is important to mention, that the inherent long lifetime (~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 ^{4}P production cross section [13, 19, 16]. 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 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, 19, 16] 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 charge 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 included for the first time, allowing for a more accurate and realistic line shape modeling [21] of both metastable and prompt Auger lines.

IV New experimental results

Fig. 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: $1s2s^2\ ^2S$, $1s2s2s\ ^4P$, $1s2s2p\ ^2P_-$, $1s2s2p\ ^2P_+$ 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 ($1s \rightarrow 2l$) 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 Fig. 3 (c) we show the extracted ratios $R = {}^4P/{}^2P$ and $R' = {}^2P_+/2P_-$. 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.

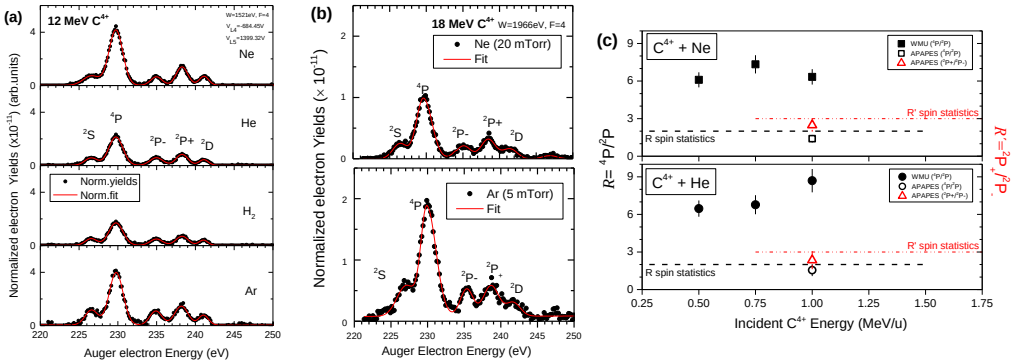

Figure 3 (a): Measured zero-degree Auger emission spectra for 12 MeV C^{4+} mixed beam ($1s^2$+$1s2s\ ^3S$) state in collisions with Ne, He, H_2 and Ar. The resulting Auger lines have been identified as belonging to the three-electron electron states $1s2l2l'\ ^{2,4}L$ indicated. The spectra have been 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 **(α)** but for 18 MeV C^{4+} beam in collisions with Ne and Ar gas targets. **(c):** Experimentally determined ratios (left scale) for $R = {}^4P / ({}^2P_+ + {}^2P_-)$ and (right scale in red) for $R' = {}^2P_+/{}^2P_-$ 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.

V Summary and conclusions

It is obvious from Fig. 3 (c), that the already published [16] values for R are approximately 2-4 times higher than our new results depending on target. For the case of the R' ratio though, fairly good agreement is found with the expected spin recoupling value of 3 for both 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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