Chapter 1

Introduction

1.1. Highly Charged Ions (HCI)

The Physics of highly ionized atoms is not only a field of extraordinary richness in specific physical phenomena but also a part of atomic physics that cross-correlates with many other scientific disciplines such as astrophysics, plasma physics, heavy ion physics, etc. Apart from its pure scientific importance, the physics of highly charged ions has also strong impact on research in several applied sciences and technological areas (for example in fusion research and material science) which provides a further stimulus for the development of this field.

Highly charged ions are those which have the spectroscopic symbol $z > 5$, where $z = Z - N + 1$. Here, $Z$ is the nuclear charge of the ion and $N$ is the total number of electrons. The functional definition of a highly charged ion varies. To many, it refers to any atom that is missing more than one or two electrons. To others, several dozen electrons must be missing before the label “highly charged” is used. HCI is an atom that has been stripped of a large number of electrons ($Q >> 1$), so that the total energy yielded ($E_o$) during re-neutralization is outside the realm of ordinary experience with laboratory ions ($E_o >> 10$ eV).

The definition overlaps with what are frequently referred to as multiply charged or multicharged ions at the lower end of this spectrum (typically $Q = 2–9$,
with $E_0 < 1000$ eV), as well as what are some times called very highly charged ions at the upper end of the spectrum (e.g., $Q = 92$ with $E_0 \sim 750000$ eV). The tremendous variety of HCIs makes almost every generalized conclusion and rule of the thumb in the field, but it also opens up an enormous range of possibilities for discovery.

1.1.1. Overview of HCI

Pioneering work in the study of multiply charged ions started as early as the 1920s when Bowen and Millikan investigated spectra of the Na I isoelectronic sequence up to CI VII produced in a condensed vacuum spark [1]. For many years, spectroscopic studies were a central topic in the investigation of multiply charged ions, motivated by the challenge of testing various theoretical predictions within quantum-mechanical concepts and bridging the gap between optical and x-ray spectra. A good account of these early investigations of the structure and spectra of highly charged ions can be found in the reviews by Edlen [2,3]. The information on the energy levels of these ions, with references to the line classification on the work, are contained in the well-known compilation of Moore [4].

A new era in the studies of the structure and spectra of highly ionized atoms began with the discovery by Edlen and Tyren [5] of so called satellite lines in the spectra of charged ions, on the essentially new elements in these spectra with respect to the neutral atoms. This discovery and its explanation is fundamental to the analysis of the radiation from highly charged ions and its use for diagnostic purposes.

The recent experimental progress in highly charged ion physics has been connected with the important developments in the construction of laboratory sources of multiply charged ions such as magnetic fusion devices, laser produced plasmas, beam-foil sources, newly developed ion sources, charged particle accelerators, paralleled with advances in the experimental tools and methods used
for studying highly charged ions and their collision processes (high-resolution spectrometers, detectors, ion traps, etc.). Spacecraft-based studies, initiated in the 1960s, have provided considerable information on highly charged ions in hot astrophysical plasmas. The experimental progress has been complemented by significant theoretical developments in the description of the structure and collision physics of highly charged ions. Both the degree of sophistication of theoretical models and the availability of powerful computing facilities have considerably increased the accuracy of theoretical predictions.

Most of the universe consists of highly ionized matter [6]. Because it is exceedingly rare on Earth and because we are blindfolded from observing cosmic sources by the relatively high x-ray absorption of our atmosphere, the scientific study and application of highly ionized matter has been limited. Atomic physics and conventional ion beam technologies, for example, were developed in the virtual absence of laboratory access to highly charged ions. Today, however, powerful devices are available that can preferentially produce any ionization stage of any naturally abundant atom. Some of these devices [7] are small enough to fit on a tabletop. Others are huge devices that produce ions traveling with comparable speed of light [8,9]. These two extremes each have their own particular applications, but they share the property of providing a window into a part of the universe that is still relatively unexplored and that can be expected to impact a variety of fields. More details and breadth of coverage of the fundamentals can be found in comprehensive reviews and conference proceedings [10–18].

1.1.2. Basic Features of HCIs and their Interactions

The specific properties distinguishing the highly charged ion from the neutral atom are mainly due to the unshielded Coulomb field of the nucleus of the ion. It’s effects show not only in the structure of the ion, but also in its interactions with other atomic particles and with the electromagnetic field. The
structure of few-electron highly charged ions is considerably affected by relativistic effects in the electron motion and the absence of any "pure" angular momentum coupling scheme. The formation of the excited states of multiply charged ions is frequently characterized by the high angular momentum of these states and their decay takes place not only by allowed processes but also through severe violation of the normal selection rules. The typical radiation emitted by highly ionized atoms falls in the vacuum ultraviolet and x-ray wavelength regions. One important characteristic of the collisions of highly charged ions with atoms is the great variety of processes which may occur. A highly charged ion brings into the collision a significant amount of additional potential energy which can be disseminated through a large number of inelastic reaction channels: creation of excited states, autoionizing states and (even copious) production of secondary electrons are the most prominent examples of the results of a collision events.

1.1.2.1. Size of HCI

Perhaps the most fundamental and physically tangible aspect of an atom is its size (spatial extent of the electronic wave function). The great diversity of physical properties exhibited by the atoms across the periodic table emerges essentially from variations in the size and shape of the wavefunction. It is perhaps remarkable, then, that all atoms are roughly of the same size: a few tenths of a nanometer. This “typical size of an atom” is the first rule of thumb that must be abandoned in making the shift from neutral atoms to highly charged ions U^Q^+, which has a wavefunction that is nearly 100 times more spatially compact than that one can expect to find among HCIs.

A simple isoelectronic scaling law for one-electron ions predicts that the size of the wavefunction (Bohr radius= R) varies as the reciprocal of the ion charge

\[ R \sim 1/Z \sim 1/(Q+1) \sim 1/Q \text{ for } Q \gg 1. \] (1.1)
For very highly charged ions, the wavefunction size becomes so small that one must begin to think about the ions in a qualitatively different way. The simplistic view of an HCI as a tiny Bohr atom with a charge is inadequate because the relevant length scales enter a new regime. Consider the hydrogen atom isoelectronic sequence. In the atomic limit, the system has planetary analogies that can be quite useful for gaining intuition. The electron orbits and nucleus at a characteristic distance that are large compared to both the spatial extent of the nucleus and the Compton wavelength of the electron (the fundamental length scale at which the electron ceases to behave as a point particle with finite charge). The ordinary hydrogen atom, like the solar system, is mainly empty space. At the high end of the isoelectronic sequence, however, the Bohr radius ($R \sim 50/Z$ pm) falls below the Compton wavelength (2 pm). Under these conditions, single-particle quantum mechanics begins to break down and semiclassical reasoning based on it becomes of limited value. Indeed, even the classical concept of a central Coulomb potential breaks down to some extent. Quantum field theory is required to describe the system. The resulting new picture is one in which the structure of the vacuum space itself is significant. The concept of empty space is replaced by one in which everything is bathed in a sea of virtual positron-electron pairs popping in and out of existence within the small window of time during which the Heisenberg uncertainty principle allows energy conservation to be violated. At short distance scales, it becomes apparent that the virtual sea of charge from the vacuum becomes polarized and screens the actual “bare” charge of an electron. The closer one gets, more the screening is avoided and the higher the electron charge appears to be. As the electron continues to “decloak” from the vacuum at increasingly shorter length scales, the apparent charge that it carries, rises significantly above the conventional value of $1.6 \times 10^{-19}$ C and ultimately approaches its bare value of infinity. The conceptual jump from a hydrogen atom to hydrogen-like uranium ion is perhaps as great, or
greater, than the jump from a classically orbiting planet to a quantum mechanical atom. A more comprehensive introduction to the quantum field theory of HCIs can be seen in the reference [19].

The reduction in size of an HCI with increasing Z results in a tremendous compression of the wavelength density at the upper end of an isoelectronic sequence. The above scaling law for atomic size predicts that a hydrogen–like (N=1) uranium atom (Z=92) has an electronic density that is 780000 times higher than that of hydrogen atom. This compression of the wave function into the space near the nucleus dramatically alters the relative importance of various physical effects that determine the atomic structure.

1.1.2.2. Kinetic Energy of HCI

Two different types of energies associated with ions, potential and kinetic, are sometimes confused particularly when discussing beams of highly charged ions. Conventional ion beams used in the microelectronics industry or in materials science are comprised of singly charged ions with a kinetic energy in the keV to MeV range. This kinetic energy dominates the interaction of such ion beams with surfaces and hence the internal (potential) energy liberated when the ion neutralizes itself upon contact with the surface is usually neglected. Since conventional ions carry only about 10 eV of potential energy (the ionization potential). It is neglected in a very good approximation. For beams of highly charged ions in the same kinetic range, however, the relative importance of kinetic energy to potential energy is reduced or even inverted sometimes by a large factor. Implications of an unusually large potential energy from application point of view is discussed in the reference [20].

1.1.2.3. Potential Energy of HCI

There are two types of potential energy that are distinct for HCIs: the ionization energy and the neutralization energy. For an ordinary ion, these two
are identical in magnitude, but for HCIs they can differ by more than a factor of ten. This is because ionization energy is the energy required to remove one electron, producing the charge Q+1 from an ion with one lower charge, while neutralization energy is the energy released in replacing all of the missing electrons. The ionization energy is most relevant to the production of the ions which typically occurs in a step-wise process (one electron removed after another) while the neutralization energy is more relevant to the impact of ions on surfaces.

1.1.3. Spectroscopy of Highly Charged Ions

Experimental and theoretical studies of the structure of HCIs belong to the most rapidly developing areas of contemporary atomic physics. In the 1970s and 1980s a number of experimental developments appeared which now make it possible to produce practically any ionization stage of any chemical element, usually by applying photon or electron spectroscopy. The experimental progress has been matched by similar advances on the theoretical side. The latter include a deeper understanding of the important physical effects which determine the structure of HCIs as well as the possibility of utilizing the great computational capabilities that are available nowadays.

In the monograph “The theory of atomic structure and spectra” Cowan (1981) summaries the progress made in the analysis of atomic spectra. Of the 5460 spectra that are possible for 104 elements (including all ionization stages), only 1002 (of 99 elements) were at least partially analyzed in 1979, twenty years earlier the corresponding numbers were 511 and 87. A closer study shows that the information is particularly scarce for highly ionized heavier atoms.

HCIs have several properties that differ from those of neutral and few times ionized atoms. Since the nuclear charge Z greatly exceeds the charge of the remaining electrons, the electrostatic interaction is predominantly central. This might lead to the conclusion that the structure of HCIs is similar to that of neutral
hydrogen. However, there are some resemblance, certain important difference also exist. For example, the high value of Z causes a contraction of the inner shells while the valence electrons will be less localized. There are also large magnetic effects which cause the fine structure splitting to exceed the electrostatic gross structure separation. The allowed electric dipole (E1) transitions, which are predominant in neutral and few times ionized atoms, will encounter strong competition from forbidden transitions, i.e. magnetic dipole (M1), magnetic quadrupole (M2), electric quadruple (E2) and two photon decay (2E1). The transition rates for the forbidden decays scale with higher powers of Z than that of E1 transitions. For sufficiently high values of Z, the forbidden transitions may therefore dominate over the allowed ones. The effects of quantum electrodynamics (QED) also scale with higher powers of Z and their importance grows in HCIs. Even the effects of the nuclear structure manifest themselves in case of highly stripped atoms. A theoretical description of all such effects would therefore involve the use of relativistic quantum mechanics including the accurate treatment of electron–electron correlation. This is possible (in principle) within the framework of the Dirac formalism for a many electron atom using the multiconfiguration Dirac–Fock (MCDF) approach. However, the QED effects must also be accurately calculated. These problems become particularly challenging when the various effects (electron correlation, relativity, QED, etc.) have comparable magnitudes because in this case simplification based on perturbative treatments may not be adequate [21]. Accurate experimental data provide useful tests of the merits and possible shortcomings of the various theoretical and computational methods which are applied to describe and predict the structure of HCIs. Rather than being exotic, the highly ionized systems dominate high temperature environments such as solar corona and stellar and laboratory plasmas and thus almost all matter in the universe is in ionized state. In such systems, the electron binding energy is very large and the strong coulomb
field has a long-range intensity that enhances interaction cross sections. The reduced electron screening causes inner shell effects to become more important. All of these properties are depending on Z which can be treated as controllable experimental parameter if a sufficiently large and reliable data base can be followed along an isoelectronic sequence. To prescribe these systems, theoretical methods must sometimes undergo conceptual and computational refinements subject to experimental verification. Furthermore, the accurate specification of wavelength and energy level data does not insure correct predictions of transition probabilities and lifetimes. Measurement of the lifetimes are particularly important since they provide absolute rate values necessary to normalize relative transition probabilities obtained by time–integrated techniques [22–26].

Experimental and theoretical data for HCIs are needed for the diagnostics of astrophysical and laboratory plasmas. For more than 40 years, it has been possible to record the spectrum of the sun in the ultraviolet and x-ray regions by means of spacecraft–based observation. The spectra show transitions from very highly charged ions of many lighter elements up to Ni (Z=28). These observations have revealed a large number of radiative transitions, not previously observed in the laboratory, thereby stimulating much activity in theoretical and experimental atomic spectroscopy.

The spectra of HCIs contain important information about plasmas macroparameters (electron and ion temperature and density, charge–state distribution, etc.) and therefore, provide an important diagnostic tool for the investigation of hot laboratory and astrophysical plasmas. As a diagnostic tool, high resolution spectroscopy of multicharged ions has proved to be an extremely useful and sometimes, even the only possible method for measuring these parameters.

The novel techniques, involving recoil from ion–atom collision experiments or very highly ionized atoms from modern ion sources like electron
beam ion source (EBIS), electron beam ion trap (EBIT), electron cyclotron resonance (ECR), and storage rings, etc. have been successfully tested. Recent advances in heavy ion beam technology make it possible to produce very highly ionized atoms up to fully stripped uranium U^{92+} in the very wide kinetic energy range from a few eV up to more than 20 GeV.

The spectra of multicharged ions possess a number of specific properties essentially distinguishing them from the spectra of neutrals. Among these properties one should mention the following:

(i) The shift of radiation spectra from infrared and visible to the vuv and x-ray region,
(ii) The growth of the ionization potentials up to several hundred or even thousand eV,
(iii) An increase of the multiple splitting proportionally to $z^a$, where $z$ is a spectroscopic symbol of an ion.
(iv) A deviation from the L–S scheme of the angular momentum coupling towards an intermediate and JJ–coupling scheme.
(v) An increase of the spectral line intensities corresponding to forbidden transitions due to relativistic effects.
(vi) The presence of satellite lines of multicharged ions connected with the radiation decay of autoionizing states.

The long range Coulomb force of an ion influences also the collisional properties of multicharged ions. The cross sections are proportional to the factor $Z^a$. For electron–ion and ion–ion collisions $a<0$, while for ion–atom, ion–molecular and radiative processes $a>0$. In some cases the factor “$a$” can be even much larger than unity. Therefore, the cross sections involving multicharged ions strongly depend on the collision partner.

High temperatures or intense photon fluxes create highly charged ions in astrophysical objects such as solar corona, x-ray emitting binary stars, supernova
remnants, etc. The atomic characteristics of these ions determine x-ray and uv spectra as well as heating and cooling rates and opacities of the objects [27]. The presence of highly ionized species in plasmas, presents a significant energy-loss mechanism in fusion devices, is used for diagnostic purposes [28].

The structure and spectra of highly charged ions in laboratory plasmas have been the subject of several reviews and monographs from an experimental [29–32] and theoretical [33–35] point of view. The intensified spectroscopic research of some selected isoelectronic sequences are caused by the interest to develop x-ray and uv laser [36–38].

Atomic collision physics, including electron–ion, ion–atom and ion–ion collisions, has also dramatically developed. The experimental and theoretical problems of elementary processes, involving multicharged ions, have been considered in several monographs [39–43] and conference proceedings devoted to the physics of highly charged ions [44,45].

The need of recommended data for different physical applications has led to the creation of several large atomic data banks organized for storage and exchange of radiative and collisional characteristics of multicharged ions. Among them are the NIST data bank [46], the Belfast atomic data bank [47], the Opacity Project data bank [48], ALADDIN (IAEA) [49], AMSTORE [50] and others. The development and availability of super computer facilities has made it possible to create computer codes for calculation, with high accuracy, of the atomic wave functions, energy levels, transition probabilities, cross sections and rate coefficients with high accuracy some of these are SUPERSTRUCTURE [51], MCHF [52], AUTOSTRUCTURE [53], CATS [54], GRASP [55], AUTOLSJ [56], ATOM, MZ [43] and others.

1.1.4. Isoelectronic and Isonuclear Sequence

To explore the full range of phase space spanned by HCIs, one might first select a particular elemental species (atomic number Z) and then remove
sequentially the number of electrons \((Q=1, 2, 3..)\) to produce a series of ions with the same nucleus but a variety of \(N\)-electron structures \((N=Z-Q)\). This type of phase space cut through the \((Z,Q)\) space of all possible HClEs is called an isonuclear sequence.

From the point of view of theory, however, scaling laws are often easier to understand by fixing the electronic number \(N\) and varying the species \(Z\). Data presented in this way are called isoelectronic sequence. Conceptually, one may think of an isoelectronic sequence as starting with a particular neutral atom and asking how the electronic properties of that atom changes as the nuclear charge is increased in a series of unit steps.

### 1.2. Beam–Foil Spectroscopy

In the early 1960s Kay [57] and Bashkin (58) realized the atomic physics potential of fast ions from particle accelerators. In a typical experiment, the accelerated ions are magnetically analyzed and then directed through a thin carbon foil or a gaseous target. The collision with the target atoms usually leads to further ionization as well as excitation of the fast ions. This method, often called beam–foil spectroscopy (BFS), is characterized by good time resolution typically \(10^{-10}\)s.

A variety of ion accelerators have been utilized in BFS research. At low ion energies, typically less than 0.5 MeV, isotope separators are common whereas the range 0.5–6 MeV can be covered with electrostatic accelerators like Van de Graaff generators. The tandem versions of which may provide ion energies as high as 200–300 MeV. In tandem accelerator, the ion source, usually based on the sputtering process, produces negative ions which after the first acceleration phase undergo multiple stripping and then accelerated to the final kinetic energy. Even higher ion energies, up to several GeV, can be reached using the new generation of heavy ion accelerators such as the tandem cyclotron (GANIL) at Caen, the heavy ion linear accelerator UNILAC in Darmstadt and the BEVALAC
accelerator facility in Berkeley.

The analyzed beam currents from the ion accelerators are usually in the range 0.01–10 µA. The beam particle density is thus quite low as compared with the density in most other laboratory light sources. However, there is some compensation by the fact that BFS is a continuous light source whereas most other sources for highly ionized atoms operate in a pulsed mode with low duty cycles. Furthermore, at the low densities inter–ionic fields are negligible and recombination and stimulated emission are absent.

More extensive discussions of the beam–foil method can be found in a monograph [59] and several review articles [60–65]. Recent variations and modifications of BFS include the excitation of fast ions with radiation from a laser or with a gaseous target (instead of the foil), as well as the use of recoil ions and the development of advanced ion sources which directly produce highly stripped positive ions. Violent collisions between highly charged, fast and heavy projectiles from an accelerator and target atoms can be exploited not only in terms of projectile excitation but also be studying the target atoms after the interaction [66,67]. In a single collision, the fast ion can remove many electrons from the target atom while transferring very little kinetic energy to it. Thus the energy deposited to the electrons may be several keV whereas the recoil energy given to the target nucleus is of the order of a few eV.

During the last twenty years, beam–foil spectroscopy (BFS) has been instrumental to significant technical advancements in the production, control and selection of beams as well as their spectroscopy [59]. It has to its credit a number of remarkable achievement in form of conventional (static) as well as non-conventional (dynamic) photon and electron spectrometers.

The beam–foil method is one aspect of a more general research area of atomic physics often called accelerator based atomic physics. In these fast beam experiments many important structure and collision parameters associated with
both the excited projectiles and target atoms are measurable.

Beam–foil technique has been used to provide information on the structure and decay rates of atoms and ions of many elements in varying stages of ionization. This method is very simple and direct one for measurement of the lifetime of excited states in atoms and ions. This is one of the main advantages of the BFS technique which in contrast to most other lifetime techniques which are only applicable to neutral, singly or sometime doubly ionized atoms. The lifetime of excited states in atoms and ions are in the range of $10^{-8} - 10^{-11}$s and such a short lifetime can be determined by BFS in a straightforward way. However, this technique often suffers from cascade and blending problems that reflect on the values of experimentally derived lifetimes. It has been noted that, in order to obtain reliable lifetimes in highly charged ions through beam foil excitation, the condition must be set so that the charge state under investigation is well below the average of the foil emergent beam [68]. To solve the blending problem, Nandi et al [69] have developed a new technique which has been used in the present work. Beam–foil quantum beat phenomena were observed in mid sixties and attributed to interference effects arising from the radiation decay of two or more coherently excited and close-lying levels of a foil-excited atom to a common lower level [70]. The coherent excitation is brought about by the impulsive nature of foil excitation process. During the early 1970s, spectral and lifetime measurements were made by the university of Tennessee–Oak Ridge National Laboratory group on foil excited ions that decayed via an Auger emission process (autoionization) rather than radiation excitation [71–74]. A number of problems have been investigated with BFS. These are as follows.

(a) Radiative transitions and energy levels in atoms and ions,
(b) Lifetimes of excited levels and atomic transition probabilities,
(c) Auto–ionization mechanisms,
(d) Stark and Zeeman effects,
(e) Atomic fine structure (fs) and hyperfine structure (hfs),
(f) Lamb shifts in one and two–electron system,
(g) Atomic collision mechanisms, etc.

Such problems can generally be tackled in various other ways but many experimental approaches are limited to neutral or a few times ionized atoms. One of the main merits of BFS is that quantitative studies of (a)–(g) can be extended to very highly stripped atoms.

In fact, the accuracy of such measurements are dependent on the complexity of the scheme of cascade transitions that repopulate the levels of which the lifetime is being determined. The most successful method to deal with this problem is the so called arbitrarily normalized decay curve (ANDC) method [75]. It relies on the simultaneous analysis of intensity decay curves for both the transition from the level under study and all its important direct cascades.

1.2.1. Atomic Transition Probabilities and Lifetimes

The determination of atomic transition probabilities and lifetimes is an active research area as may be seen from three indicators: (a) the number of research papers since the publication of first general bibliography [76] in 1962 has grown from 650 to nearly 3000; (b) the data known in 1962 covered roughly $10^3$ spectral lines, a number which has increased by an order of magnitude to roughly $10^6$; (c) the accuracy of the numerical data has significantly improved.

The experimental techniques, from which the majority of atomic transition probability and lifetime data are derived, are the following: Experimental transition probabilities are directly determined through emission, absorption and anomalous dispersion by Hook technique. Atomic lifetimes are directly determined by beam foil spectroscopy, the delayed coincidence technique and the Hanle–effect (or zero–field level crossing) technique.

Theoretical calculations, which are commonly used, are self–consistent field (Hartree–Fock) calculations in various levels of refinement, nuclear charge
expansion techniques and semi-empirical calculation. In addition, regularity studies have yielded many new data.

1.2.2. Lifetime Measurements Using Time of Flight Technique

One of the most useful applications of beam–foil technique involves the study of time–dependent decay processes by a time of flight technique that utilizes the excellent time resolution produced by fast unidirectional beams and which also scale short decay times into small measurable decay lengths. The lifetime of a particular state of an ion in the beam is measured by studying the decay in intensity of a line associated with a transition as a function of the distance between the foil and the detector viewing region (window). Spatial coordinates are converted to temporal coordinates by dividing the constant postfoil beam velocity. The relative distance between the foil and viewing region is usually varied by translating the foil in a direction parallel to the beam axis.

The precision of individual beam–foil lifetime measurements varies somewhat depending upon the conditions pertaining to the experiment. Thus the precision of the measurement may be \( \sim 10–15\% \) when cascading complicates the data analysis. However, accuracy is possible closer to 5\% under more ideal condition where cascading is unimportant, the line is relatively strong and unblended, the energy loss suffered by beam ions is negligibly small as is often the case in high energy experiments. A particularly well–designed beam–foil lifetime experiment was performed by Astner et al [77] at relatively low beam energies in order to estimate how precise a measurement could be made with this technique under optimum conditions.

The beam–foil method has a number of unique features which permit many new types of experiments. Some of these features are rather subtle, but the time resolved nature of the decay process is so conspicuous that it is apparent why the first and most widely applied usage of this technique should be in the measurement of atomic lifetime. Because of the nearly mono–energetic
properties of the beam, the time “t” since excitation directly corresponds to the distance (x) from the foil is given by

\[ t = \frac{x}{v} \]  

(1.2)

Where the beam velocity \( v \) (mm/ns) is calculated from the equation

\[ v[\text{mm/ns}] = 13.9 \frac{(E)}{(M)^{1/2}}[\text{MeV/amu}]^{1/2} \]  

(1.3)

\( E \) is the energy of post foil beam taking the energy loss into consideration, \( M \) is the mass of the ion. In our case energy loss was calculated by using SRIM code [78].

The decrease in light intensity with distance from the foil for a spectrally resolved emission line is a measure of the rate of relaxation of the upper level and directly leads to its mean life. In the absence of repopulating by cascading transitions from higher levels, the mean life is proportional to the negative inverse of the logarithmic derivative of decay curve of emitted light.

1.2.3. Post Foil Charge State Distribution

Due to the statistical nature of charge exchange processes in the foil material, the ion emerges from the foil in a distribution of charge states (profile for each ionization stage is approximately Gaussian in shape). The mean of this distribution increases with incident beam energy and the width of the distribution tends to become greater for heavy ions. The beam-foil investigator requires knowledge of the energy dependence of these post-foil charge distributions in order to choose the optimum incident beam energy to maximize a particular ionization stage. A survey of the available experimentally measured charge state fractions for various ion has been made by Betz [79] and Wittkower and Betz [80]. However, in most of the elements no experimental data is available for the analysis. For the selection of charge state of ion, charge state fraction prediction from ETACHA code based on semiemperical scaling law have been used [81]. The predications has found out to be reliable in the required energy range [82].
1.2.4. Importance of Charge State Identification

Frequently spectral lines appear in the post foil spectrum that have not been previously classified and the first step in identifying these lines is to determine the charge of the emitting ion. Several different techniques have been developed for this purpose. The simplest method, although not necessarily always reliable, is that used originally by Kay [83]. The excitation function (line intensity vs incident beam energy) of a line is investigated and compared to energy dependence of the production of various ionization states under the assumption that charges in the line intensity with the beam energy are primarily due to changes in the production of the ion. This technique, which has the advantage that no auxiliary equipment is necessary, seems to work quite well for singly excited states but, is less reliable for multiply excited states.

Other methods of charge state identification involve the application of external electric or magnetic field to the beam–foil source. If the lifetime of the excited state is sufficiently long, ion of different charge state in the source can be spatially separated by an external electric or magnetic field. If the lifetime of the excited state is sufficiently large, ions of different charge state in the source can be spatially separated by an external electric or magnetic field before de-excitation occurs. In this case, ions of different charge states can be isolated and radiative transitions studied separately. Such technique was employed by Lennard et al [84]. If the de-excitation of the ions occur in the electric field being used for separation, a Doppler shift technique described by Carriveau and Bashkin [85] can be used. The deflecting field gives an ion a transverse velocity component. The magnitude of which is dependent upon the ionic charge of the emitter. As a consequence, techniques have also been used to identify the charge state of emitting beam ion. Cocke [86] has described experiments involving coincidence counting between x-ray photons and scattered ions. Groeneveld et al [87] and Schumann [88] described similar coincidence measurements between Auger
electron emitted in the decay of doubly excited states and the charge states of the various ion in the beam.

1.2.5. Problems Associated With BFS Technique

During the last two decades, beam-foil spectroscopy has been the major source of experimental data for the lifetime of energy levels belonging to moderately or highly ionized atoms. The only two serious problems associated with the technique are the possibility of the line blending (resulting from the low intensity of this light source and a relatively low spectroscopic resolution) and the effects of cascade repopulation on the intensity decay curves used to determine the atomic lifetimes. Once a specific line blending problem has been recognized, it can be dealt with by the usual procedures such as working in a higher order of diffraction, devoting more time to recording that spectral region using narrower slits or seeking an unblended branch from the same upper level. On the other hand, the cascade problem is inherent in the non-selective nature of the beam-foil excitation mechanism and although the use of a very low ion energy can reduce the effects of cascading [89] in practice that approach has met with mixed success [90].

Cascading is actually repopulation of decaying level of interest, we call primary level, due to deexcitation of population from the higher lying levels called cascading levels. These cascading levels are populated as a result of statistical non-selective nature of the beam-foil collisional excitation processes. Due to the repopulation of the primary level by cascading levels, the observed decay curve of the primary level is masked by the lifetimes of the cascading level. The decay curve in such cases is actually multiexponential sum that includes terms representing all the cascading levels including one describing the level of interest. In actual practice, however it is frequently possible to approximate the cascading contributions of one or perhaps two dominant components.

A much more promising approach was proposed almost 30 years ago by
Curtis et al [91], but it was little used until computer routines such as ANDC [75], CANADY [92] and were developed. These routines have been used with success on a variety of atomic systems. The fundamental concept in this technique is the simultaneous analysis of the decay curves for the primary transition (from the levels for which the lifetime is required) and all its important direct cascades, according to the first order differential equation relating to the population of the various levels involved. Obviously the technique becomes more difficult to apply as the number of important cascades increases.

1.2.6. Beam Single and Two-foil Technique

Beam foil interactions are statistical in nature so at any beam energy charge states neighboring to the charge state of interest are also populated to a considerable extent. The population of the neighboring charge states causes satellite blending problems to the parent line of interest which makes the extracted lifetime values beam energy dependent. Beam two-foil technique [93] is handy remedy to cure the satellite blending problem [69]. In this technique, the beam is first made to pass through a thicker foil which is movable. The post foil beam containing the excited states in various charge states is then made to pass through second foil which is thin and stationary. The technique can be used if the excited state corresponding to the parent line and to the satellite line had considerably different lifetime. In fact, the single-foil data and two-foil data show completely different exponential trends. By playing with the different modes of interaction and varying decay length of the parent and satellite line transitions from the single-foil and two-foil data and by using indigenously developed multicomponent exponential growth and decay analysis technique, it is possible to extract blending free lifetimes for the levels of interest [69]. The two-foil method also allows the standard beam-foil time of flight technique to be extended to shorter lifetimes down to ps [93].

In a previous study, Nandi et al [69] have used the beam single-foil as
well as the beam two-foil technique with different beam energies, to resolve satellite blending in the measurement of the 1s2p $^3P_2$ level lifetime in He-like vanadium. In the current study, the same approach is used in order to resolve satellite, as well as H-like M1 line blending and obtain a reliable lifetime for the 1s2p $^3P_2$ level in He-like $^{58}$Ni [94]. This level has been investigated with standard beam–single–foil experiments at a higher (340 MeV) beam energy [95]. As blending from the H– and Li–like lines had not been considered in the analysis of the 1s2p $^3P_2$ lifetime in He-like Ni, it has been reinvestigated in our lab. In general, this technique has the potential to substantiate further results on yet unstudied systems or systems for which the published results are in question.

References


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