Chapter 4

Lifetime of 1s2p \(^3\)P\(_2\) Level in Ni\(^{26+}\)

4.1. Introduction

Nickel is a cosmically abundant element and highly charged Ni ions are present in variety of non-terrestrial sources such as corona of sun, stellar atmosphere, clusters of galaxies and supernova remnants [1]. In this chapter, the measurement of lifetime of 1s2p \(^3\)P\(_2\) level in He–like nickel and the effect of satellite blending will be discussed in detail. Satellite line, originating from one unit lower charge state, may be blended with the line of interest leading to a systematic shortening of the measured lifetime. However, this condition can not be practically possible to resolve satellites always particularly for heavy He–like ions. As a result, the neighbouring charge states may introduce blending e.g; He–like M2 transition (1s\(^2\) 1S\(_0\)–1s2p \(^3\)P\(_2\)) can not be resolved from Li–like satellite (1s\(^2\)2s \(^2\)S\(_{1/2}\)–1s2s2p \(^4\)P\(_{3/2}\)) for Z up to 50 by the solid state detectors that are commonly used in the beam–foil experiments. Thus satellite blending may severely affect the lifetime measurement during the conventional beam–foil experiments and the fact remains unnoticed in many measurements. As for example, the lifetime of 1s2p \(^3\)P\(_2\) level in He–like nickel has been measured with standard beam–single experiment at a higher (340 MeV) beam energy [2] because blending from the H– and Li–like lines had not been considered in the
analysis [2]. Recently, Nandi et al. [3] used the beam single-foil [4] as well as beam–two-foil technique [5], appropriate for a wider range of beam energies, to resolve satellite blending problems for the measurement of 1s2p \(^3\)P\(_2\) level lifetime in He–like vanadium. In the current study, we use the same approach in order to resolve satellite as well as \(\text{H–like} \) M\(_1\) line blending and obtain a reliable lifetime for the \(1s2p \(^3\)P\(_2\)\) level of He–like \(^{58}\)Ni [6]. We have reinvestigated the \(1s2p \(^3\)P\(_2\)\) lifetime in He–like Ni taking all possible blending into account.

4.2. Theoretical Background

Fig. 4.1. shows the energy level diagram of He–like and Li–like nickel including their lifetimes and decay modes. The \(1s2p \(^3\)P\(_2\)\) level of highly charged He–like ions \((Z \geq 18)\) mainly decays through a magnetic quadrupole transition \((M2)\) that has attracted considerable interest. At low \(Z\), the \(1s2p \(^3\)P\(_2\)\) level in He–like ions decays mostly by electric dipole transition to \(1s2s \(^3\)S\(_1\)\) level. The magnetic quadrupole transition probability increases as \(Z^8\), whereas, the El transition probability increases with \(Z^4\) [2] and \(M2\) intensity supersedes El for \((Z \geq 18)\). Non–relativistic calculation of M2 decay rate has been made by Mizushima [7], Garstang [8,9], Drake [10,11] and Jacobs [12]. Relativistic correction has been calculated by Gould, Marrus and Mohr [13] and Johnson and co–workers [14–16]. The later used the relativistic–random phase approximation (RRPA) to calculate both the M2 and the El transition probabilities. The RRPA results of transition probability \(\omega\) for He–like \(1s2p \(^3\)P\(_2\)\) level in nickel are

\[
\omega_{\text{rel}}(2 \, ^3\!P_2 M2) = 1.20\text{E}10\text{s}^{-1} \quad \text{and} \quad \omega_{\text{rel}}(2 \, ^3\!P_2 E1) = 2.17\text{E}09\text{s}^{-1},
\]

corresponding to a lifetime, \(\tau_{\text{rel}} \, ^3\!P_2 = 70.6\) ps.

The branching ratios are

\[
b_{\text{rel}}(2 \, ^3\!P_2 M2) = \frac{E_{\text{rel}} \, 2 \, ^3\!P_2 M2}{E_{\text{rel}} \, 2 \, ^3\!P_2 M2 + E_{\text{rel}} \, 2 \, ^3\!P_2 E1} = 0.847
\]

\[
b_{\text{rel}}(2 \, ^3\!P_2 E1) = 84.7\%.
\]
Li–like Nickel

He–like Nickel

Fig. 4.1. Energy level diagram of He–like and Li–like nickel including their lifetimes and decay modes.
\[
\begin{align*}
\frac{b_{rel}(2^3P_2E1)}{E_{rel}2^3P_2E1} &= \frac{E_{rel}2^3P_2E1}{E_{rel}2^3P_2M2+E_{rel}2^3P_2E1} = 0.153 \\
\text{and } \quad b_{rel}(2^3P_2E1) &= 15.3\%.
\end{align*}
\]

Transition probabilities for Li-like Ni have been calculated relativistically in the intermediate-coupling scheme using Dirac–Hartree–Slater wave functions and the Moeller operator [17] which are given by

\[
\omega_{rel}2^3P_{3/2} \text{ (Autoionizing)} = 8.97 \times 10^9 \text{s}^{-1}
\]

\[
\omega_{rel}2^3P_{5/2}M2 = 1.22 \times 10^{10} \text{s}^{-1}.
\]

corresponding to a lifetime, \(\tau_{rel}2^3P_{5/2} = 43 \text{ ps}\).

The branching ratios are

\[
\text{and } \quad b_{rel}2^3P_{3/2} \text{ (Autoionizing)} = 42.35\% \quad \text{and} \quad b_{rel}2^3P_{5/2}M2 = 57.65\%.
\]

The He-like levels \(1s^22p^3P_2, 1s^22p^3P_1, 1s^22p^3P_0, 1s^22s^3S_1, \) and \(1s^22s^1S_0\) lie within an energy range of about 80 eV [18,19]. The \(1s^22s^1S_0\) level decays through a two-photon process [20,21] whereas the \(1s^22p^3P_0\) level decays to the \(1s^22s^3S_1\) level through an E1 transition in the VUV region. The \(1s^22p^3P_1\) and \(1s^22p^3P_1\) level lifetimes are of the order of femtoseconds. As a result, the only He-like levels, those may contribute to the 7.8 keV line (Fig. 4.4), are the rather long-lived \(1s^22p^3P_2\) (70.6 ps) [16] and \(1s^22s^3S_1\) (2.3 ns) [16] levels.

The \(1s^22s^22p^4P_{5/2}\) Li-like level is linked to the Li-like ground state with a transition energy 7.73 keV [18] in the vicinity of the 7.8 keV line. Whereas, a substantial decay through an autoionization channel (42.35%) [17] is possible, this level is also linked to the \(1s^22s2^3S_{1/2}\) Li-like ground state through an M2 radiative channel (57.65% [17]). The Li-like \(1s^22s^2p^4P_{5/2}\) level must also therefore be considered, in principle, in the analysis of our 7.8 keV data. The same holds for the H-like \(2s^2^3S_{1/2}\) level (lifetime 215 ps) [22] and excitation energy 8.07 keV [23]). The \(2s^2^3S_{1/2} H\)-like level decays through a 2E1 (decay rate \(3.87(09) \text{s}^{-1}\) [21]) and an magnetic dipole transition (M1) channel (decay rate...
0.78(09)\(^{-1}\) [18]). The latter slower decay that manifests itself in Fig. 4.4(c) for larger target detector distances. Although Be-and B-like Ni lines have also been observed around 7.8 keV in Tokamak plasmas [24,25], we note that these charge states do not contain levels that meet both the transition energy as well as the lifetime requirements imposed by the 7.8 keV peak.

4.3. Experimental Setup

The \(^{58}\)Ni ions used in the measurements were obtained from 15 MV Pelletron Accelerator at Nuclear Science Center, New Delhi. A collimated 3mm diameter nickel beam was excited by passage through 45 \(\mu\)g/cm\(^2\) carbon foil. Emerging x-ray were passed through a collimating system consisting of three slits as well as shielding cup and were detected by low energy germanium detector having resolution 150 eV at 5.9 keV which was placed at right angle to the beam (for details of the detector see the chapter 3). The target consists of two carbon foils one thick (45 \(\mu\)g/cm\(^2\)) and other thin (4 \(\mu\)g/cm\(^2\)). The separation was changed by moving the first foil. The movement of the foil was controlled by the plunger system consisting of three high accuracy dc linear servo activators (plunger system will discuss in the next section). Normalization of the incident flux was achieved through elastic scattering of the beam by gold foil of thickness (150 \(\mu\)g/cm\(^2\)) placed 20 mm downstream to the detector slit, recorded by two silicon surface barrier detectors that were symmetrically placed about the beam. Provision for loading a two-foil target in the setup, made it possible to measure lifetimes that disentangles the satellite blending [7]. The experiment was carried out using carbon foils with 163 MeV, 160 MeV and 156 MeV \(^{58}\)Ni beam. The experimental setup is shown in the Fig. 4.2.

4.3.1. Motor Assembly

The NSC time of flight distance measurement device (TOFDMD) consists of three DC micro actuators (Model 850 series, Newport Corporation, U.S.A).
Each of these motors can be run separately or together. The precision of their motion is better than 0.1 micro meter. The maximum range of the motors is only 12 mm which is quite sufficient for studying pico second range lifetimes. All the three motors are kept inside an aluminum housing with their axes aligned in a circle of diameter 30 mm. During the experiment, the whole housing along with the motors is kept in vacuum. The individual and simultaneous motion of the motors is used to make the target assembly parallel to each other [26,27].

4.3.2. Target Assembly

The target holder assembly of the TOFDMD device is aligned to the center of the three axes of the individual motors which is also the beam axis. The gearhead of each motor is coupled to the 6 mm thick invar rods with springs. The target holder is mounted on the free end of these three rods. The mountings are done on the insulating screws. This is done to insulate the target from the rest of the body for the purpose of the capacitance measurement between two carbon foils. The capacitance measurement technique will be discussed in the later section. Thus the target mounted at one end of the three rods, which are coupled to the axis of the motors at the other end, can be moved along the beam axis in both backward and forward directions. A beam collimator and a Faraday cup are mounted before the target and after target respectively on the fixed invar rods. The four feed-through points are mounted in the motor housing. Three feed-through are used to activate the three motors and the forth feed-through pin is used to take the signals from the collimator, target and the ground body of the device.

4.3.3. Computer Interface

The computer interface to the motors consists of a PC/XT/AT compatible controller with dedicated HCTL-1000 micro processor for each axis. The maximum I/O bus speed supported is 8 MHz. Each axis is independently
controlled by dedicated motion controller IC. Since all computation is performed internally, CPU is free to perform the other tasks. The other part consists of the 90–130/180–264 V AC 47–63 Hz external switch selectable 45 watts power supply for the three axes of the linear actuators. The module has got a 25 pin TTL compatible general purpose I/O connector with different outputs for each axis. The actuators are controlled through the PC (80286 CPU or higher) using a graphic user interface program named “Warp” which runs on any DOS (2.0 or higher) environment.

4.3.4. Target Holder Polishing Procedure

The polishing procedure comprises of three steps mainly. First step is to clean the surface by a calcium carbide coated paper. A rigorous treatment by this procedure would release all tiny dents from the surface. The next step is to polish this surface using the alumina powder. The three grades of alumina powder (coarse, medium and fine) were applied in succession. The polishing was done using a special velvet polishing cloth which is free of dust and lints. In the last step, the surface was polished by finest grade diamond powder (commercially available as diamond paste).

4.3.5. Distance Calibration

Fig. 4. 3(a) shows the capacitance measuring arrangement made inside the chamber for determination of minimum distance and to make the two targets parallel [28]. The shortest lifetime which could be measured using TOFDMD technique is of the order of the time of flight between the carbon foils for minimum gap. The precision with which the distances are measured with the NSC time of flight distance measurement device is better than 0.1micro meter. The minimum distance depends upon the alignment of the carbon foils. This also demands that both foils are straight. The minimum distance is thus using the capacitive extrapolation method. The capacitance can directly be measured.

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Fig. 4.3(a) Arrangement for the measurement of the minimum distance between the two foils FF (fixed foil) and MF (moveable foil). C is capacitance due to the two foils and $C_T$ is the capacitance of the DC filtering capacitor.

Fig. 4.3(b) A graph of $V^{-1}$ vs the distance
capacitance meter. Alternatively, one can use the technique initially used by Alexander and Bell [28]. In this technique, a given voltage pulse with fast rise time and a long decay time is applied on one of the plates of the capacitance so as to induce a charge on the other plate. This induced charge is further integrated by a charge sensitive pre-amplifier (ORTEC model 142A [29] used in the present setup) which will produce a voltage pulse proportional to the charge induced and is inversely proportional to the target distance. This voltage pulse after integration and shaping through a spectroscopic amplifier (Model 572 of EG&G ORTEC [29]), is finally digitized through a multi channel analyzer (MCA). Thus the MCA output is proportional to the capacitance and is used for calibration. The induced voltage varies with the distance of separation between the two foils (Fig. 4.3(b)). At larger distance, the variation is linear whereas it may be non-linear or discontinuous when the two foils touch each other.

4.4. Experimental Observations

We have used x-ray spectroscopy to study composition of excited states as a function of distance between foil and detector in the single-foil case and as separation between foils in the two-foil case to deduce the lifetime of 1s2p ^3P_2 level in He-like nickel. The spectrum, calibrated using a standard ^242Am radiation source, exhibits a prominent spectral line at 7.8 keV (Fig. 4.4). This peak consists of a blend of transition from He-like 1s2p ^3P_2 and 1s2s ^3S_1 levels and the Li-like 1s2s2p ^4P_{3/2} level (Table 4.3). This blending is not expected to be resolved by the detector that was used in this work. We also note the 8.07 keV associated with the M1 line 1s ^2S_{1/2} - 2s ^2S_{1/2} transition in H-like ion (Table 4.3). There are some unresolved peaks in the low energy region between 1.3 and 2.4 keV. This structure can be fitted to four peaks at 1.5, 1.8, 2.0 and 2.2 keV (Fig. 4.4). A preliminary investigation showed that lifetimes for the first three peaks fall in a 100–125 ps range. Two of these lines have been tentatively associated with
Fig. 4.4. Single-foil energy spectra at (a) 0.15 mm, (b) 4.8 mm and (c) 7.5 mm target-detector distance. Line energies in keV, beam energy 163 MeV, thickness of foil 45 μg/cm², energy per unit channel 4.457 eV, Energy resolution; 165 eV at 5.9 keV (static source). The figure clearly shows that as the target-detector distance increases, the peak around 8 keV is split into two peaks.
Li-like Ni transitions. Clearly better spectral resolution is required to identify conclusively these unknown transitions. A high-resolution x-ray spectroscopy setup is also being developed in our group in an effort to investigate the relative strengths of the blending lines at 7.8 keV and also to identify the unknown transition between 1.3 and 2.4 keV.

The normalized intensity variations of the 7.8 keV peak with single-foil and two-foil measurements at 163 MeV are shown in the Fig. 4.5. The exponential decay (Fig. 4.5(a)) trend in case of single-foil measurement may be represented in terms of an apparent decay time. In the two-foil (Fig. 4.5(b)) measurement, we note that the intensity of the line under investigation grows as the separation between the two-foils increases.

4.5. Data Analysis and Results

Several charge states are produced due to ion-atom collision involving electron capture and loss processes when isotopically pure ion beam of certain charge state and energy passed through a foil. The charge state fractions for the $^{58}\text{Ni}^{+12}$ beam used in this work, obtained with the code ETACHA [30], are shown in the (Table 4.1) where energy losses in the foil were considered in the calculation. Those charge state fractions are useful as they provide an indication as to the type of ions that are present when the beam leaves the carbon foil. Results of experiments performed at GANIL with 10 MeV A$^{-1}$ ions [30] agree with equilibrium as well as non equilibrium predications of theoretical charge state fractions obtained with the code ETACHA. However, no such studies exist for Ni beam in the range of 2-5 MeV A$^{-1}$. Interestingly, Berry et al [31] have used low energy 1.6 to 2.5 MeV A$^{-1}$ Cl beams to observe He-like 1s2s $^3\text{S}_1$ - 1s2p $^3\text{P}_2$ and 1s2s $^3\text{S}_1$ - 1s2p $^3\text{P}_0$ transitions. This observation is consistent with the ETACHA predictions shown in (Table 4.2) and strengthens our confidence in the validity of the charge state fractions reported in (Table 4.1) for the $^{58}\text{Ni}^{+12}$ beam.
Fig. 4.5. Normalized count rates for the 7.8 keV peak (beam energy 163 MeV) as a function of (a) the distance between the foil and the detector (single-foil) and (b) the separation between the two-foils (two-foil experiment, distance between the second foil and the detector fixed to 2.5 mm). Solid lines represented a single exponential fit to the data (curve a) and a fit to the data using Eq. 4.4 (curve b, see text) respectively.
used in this work. It may also be seen from Table 4.1 that the H–like, He–like and Li–like charge states account for less than 30% of the ions emitting K x-rays. All the four lines shown in Table 4.3 contribute to 7.8 keV peak, depending on the experimental conditions (foil thickness, beam energy and target detector distance) show only single component in the limited travel of 10 mm. Thereby, these curves were fitted with single exponent and the apparent decay times $\tau_s$ determined in this manner are shown in Table 4.4. Since the charge state fractions at the beam energies 156–163 MeV do not differ significantly (Table 4.1), the average apparent decay time from the single–foil experiments is also reported in Table 4.4.

In the two–foil case, we focus on the excitation–de–excitation processes of the ions in two regions, viz., (i) the variable foil separation, $x$, between two–foils and (ii) the fixed distance, $d$, between the second foil and the detector slit. The deexcitation phenomenon in $x$ is identical to the single–foil situation. However, due to interaction with the second foil the relative intensity of each decay component may be altered and as a result the effective apparent decay time $\tau_1$ may differ considerably. All the levels decaying radiatively can be written as $I'e^{-x/\tau_1} e^{-d/\tau'_1}$. Here $\tau'_1$ is the apparent decay time but different from $\tau_1$ as the relative strengths of various time components change due to the interaction in the second foil. Although lifetime $\tau'_1$ ought to change for every value of $x$, we approximate it to have a fixed value at this stage. The He–like nickel ground state, so produced due to the photon decay of all the states, might have certain probability to reproduce any of these states (Fig. 4.1 and Table 4.3). Therefore, it leads to a growth term of $I''_1(1-e^{-x/\tau_1}) e^{-d/\tau'_1}$, where $\tau''_1$ is a fixed effective lifetime containing different strengths of all three states produced due to the interaction of He–like nickel ground state and second foil $\tau'_1$ may not differ much from $\tau''_1$. The autoionizing $1s2s2p^4 P_{3/2}$ Li–like Ni level decays through
both autoionization as well as radiative processes and the branching ratio for the autoionizing channel is rather large (57.65%) [17]. The ground state of He–like nickel produced at x due to the autoionizing transition $1s^2 \, ^1S_0 \rightarrow 1s2s2p \, ^3P_{3/2}$ can generate all the four states (Table 4.3) due to the collisions with second foil. Therefore it contributes to a growth term as $I''_2 (1-e^{-\rho\tau_2}) e^{-\rho\tau_1}$, where $\tau_2$ is the pure lifetime of $1s2s2p \, ^3P_{3/2}$. Interestingly, the $1s2p \, ^3P_2$ state has an E1 branch (Fig.4.1) to $1s2s \, ^3S_1$ which could regenerate the $1s2s2p \, ^3P_{3/2}$ level while passing the second foil by capturing an electron in 2p shell. Such an electron capture process results in another growing term $I'_3(1-e^{-\rho\tau_3}) e^{-\rho\tau_2}$, where $\tau_3$ is the lifetime of $1s2p \, ^3P_2$ level. It may be noted that the $1s2p \, ^3P_2$ and $1s2s \, ^3S_1$ states decaying to $1s^2 \, ^1S_0$ will have to undergo both excitation and capture within the second foil, in regenerating $1s2s2p \, ^3P_{3/2}$ state which is very unlikely in a single collision condition [32]. Further there is a certain probability of $1s2s \, ^3S_1$ exchanging to triplet–p and versa. It would also lead to a growing component as $I'_4(1-e^{-\rho\tau_4}) e^{-\rho\tau_2}$ where $\tau_4$ is 2.3 ns and $\tau'_4$ an effective and fixed lifetime which may be different from $\tau_4$ because the resultant state is a mixture of triplet–s and triplet–p levels [5]. We note however that an additional growing component due to the H–like M1 transition should be considered. The H–like, which was resolved in Nandi et al [3] on vanadium, is also resolved at larger target–detector distances in the current study (Fig. 4.4(a)). This line is not resolved for small and intermediate target–detector distance (Fig. 4.4(b)). The $2s \, ^3S_{1/2}$ level ($\tau_5$) can generate He–like and Li–like ionic levels by capturing one or two electrons as it passes through the second foil. Now adding all the terms together, 

\[
I(x) = I'_1 e^{-\frac{x}{\rho \tau_1}} + I''_1 (1-e^{-\frac{x}{\rho \tau_1}}) e^{-\frac{d}{\rho \tau_1}} + I'_2 (1-e^{-\frac{x}{\rho \tau_2}}) e^{-\frac{d}{\rho \tau_1}} + I'_3(1-e^{-\frac{x}{\rho \tau_3}}) e^{-\frac{d}{\rho \tau_2}} + I'_4 (1-e^{-\frac{x}{\rho \tau_4}}) e^{-\frac{d}{\rho \tau_2}} + I_5 (1-e^{-\frac{x}{\rho \tau_5}})
\]

Rearranging the first and second terms of the above equation, we get

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\[ I(x) = e^{-\lambda x} \left( I_1 e^{-\lambda d_1} + I_2 e^{-\lambda d_2} + I_3 e^{-\lambda d_3} + I_4 e^{-\lambda d_4} + I_5 e^{-\lambda d_5} \right) \] (4.2)

Since the second foil is held fixed, all the terms not involving \( x \) are constant for a given velocity. Thus redefining the intensity parameter

\[ (I_1 e^{-\lambda d_1} - I_2 e^{-\lambda d_2}) \] as \( I_1 \), \( I_2 e^{-\lambda d_2} \) as \( I_2 \), \( I_3 e^{-\lambda d_3} \) as \( I_3 \), \( I_4 e^{-\lambda d_4} \) as \( I_4 \), and so on, as \( I_6 \).

Eq. 4.2 takes the form

\[ I(x) = I_1 e^{-\lambda x} + I_2 (1 - e^{-\lambda x}) + I_3 (1 - e^{-\lambda x}) + I_4 (1 - e^{-\lambda x}) + I_5 (1 - e^{-\lambda x}) + I_6 \] (4.3)

The terms in Eq. 4.3 give only the contributions occurring during the flight in between the two foils.

Here \( I(x) \) is the intensity as a function of the distance \( x \) between the two foils. The total intensity contribution in the two-foil experiment is due to four growing components related to the presence of \( 1s2s2p \, ^4P_{s1/2} (\tau_2) \), \( 1s2p \, ^3P_2 (\tau_3) \), \( 1s2s \, ^3S_1 (\tau_4) \) and \( 2s \, ^3S_{1/2} (\tau_5) \) levels having theoretical lifetime of 43 ps [17], 70.6 ps, 2.3 ns [16] and 215 ps [22] respectively (Table 4.3). The average apparent decay time determined from the single-foil experiment is 85 ± 3 ps (Table 4.4). This result is larger than the theoretical \( 1s2p \, ^3P_2 \) lifetime (70.6 ps) and suggests possible blending due to Li-like \( 1s2s2p \, ^4P_{s1/2} \) and H-like \( 2s \, ^3S_{1/2} \) lines. The growth of the counts in the 163 MeV two-foil experiment at small separation (Fig. 4.5) implies that the growing component supersedes the decaying. If an apparent decay time \( \tau_c \) for \( 1s2s2p \, ^4P_{s1/2}, 1s2s \, ^3S_1, 2s \, ^3S_{1/2} \) is determined from the two-foil data, the (collective) contribution of these components can then be used in the analysis of the single-foil data in order to extract the \( 1s2p \, ^3P_2 \) lifetime. On the basis, Eq. 4.3 is written as

\[ I(x) = I_1 e^{-\lambda x} + I_6 (1 - e^{-\lambda x}) \] (4.4)

Where \( \tau_c \) is an apparent decay time associated with Li-like \( 1s2s2p \, ^4P_{s1/2}, \) He-like \( 1s2s \, ^3S_1 \) and H-like \( 2s \, ^3S_{1/2} \) levels.
A least square fit of the two-foil data at 163 MeV using the above Eq. 4.4 was performed. In the fitting procedure, apparent decay time $\tau_1$ was fixed to the value $\tau_1 = (84\pm5$ ps) obtained from the single-foil measurement. The apparent decay time $\tau_c$ is then determined to be $130\pm12$ ps (Table 4.4, beam energy 163 MeV).

Finally, in order to disentangle the contribution of the $1s2s2p \, ^4P_{3/2}$, $1s2s \, ^3S_1$ and $2s \, ^2S_{1/2}$ levels from the apparent decay time $\tau$, determined from a one-exponent fit of the single-foil data and thus obtain a value for the $1s2p \, ^3P_2$ lifetime. The best fit gave the values of $I_1 = 43.35\%$ and $I_c = 57.65\%$. We have repeated the analysis on the single-foil decay curve at 163 MeV. The decay curve was fitted this time with two rather than one, exponents as follows

$$I(x) = I_1 e^{-x/\tau_1} + I_2 e^{-x/\tau_c} \quad (4.5)$$

In this fitting procedure, the apparent decay time $\tau_c$ due to $1s2s2p \, ^4P_{3/2}$, $1s2s \, ^3S_1$ and $2s \, ^2S_{1/2}$ levels was kept fixed at $130\pm12$ ps (Table 4.4) and a value $70\pm5$ ps was obtained for $\tau_1$ associated with the $1s2p \, ^3P_2$ lifetime as shown in the (Table 4.5).

The data at 160 MeV and 156 MeV were analyzed in similar way to yield apparent decay times $\tau_1$ and $\tau_c$ as shown in the (Table 4.4) and eventually $1s2p \, ^3P_2$ lifetime in the (Table 4.5).

The velocity of the post-foil beam was calculated from the beam energy at the exit of the foil using the code SRIM [33]. The uncertainty in the beam velocity is less than 1%. The x-ray detector and the beam velocity are at $90^\circ\pm1^\circ$ to eliminate the Doppler effect from the measurement. It results Doppler shift tending to zero. The parallel translation of the first foil relative to the second has been achieved by moving individual actuators until the highest capacitance was obtained. Uncertainties in the $\tau$, values are therefore only due to the statistical
uncertainties in the line intensities. Uncertainties in $\tau_e$ arise as a result of approximations introduced in the fitting procedures (Eq. 4.4) as well as from statistical uncertainties in the line intensities. The total error in $\tau_e$ was accounted for by introducing three statistical uncertainties in the line intensity. In the subsequent two-exponent fitting of the single-foil data using Eq. 4.5, the uncertainty in $\tau_e$ was accounted by introducing two statistical uncertainties in the line intensities. Therefore, within the iterative fitting procedure employed in this work, the uncertainties in the quoted lifetimes in (Table 4.4 and 4.5) represent on standard deviation only. This choice restricts the reduced $\chi^2$ close to unity in both the cases. The average lifetime for the 1s2p $^3P_2$ level determined in this experiment is therefore 70.3±3 ps (Table 4.5). This result is consistent with previous theoretical (70.6 ps [16]) and the experimental (70.3±3 ps [2]) values.

4.6. Discussion

In a previous study [2] the Ni data are fitted with two exponential and a constant background. The first component, corresponding to 1s2p $^3P_2$ [2], is associated with a lifetime of 70±3 ps in agreement to the average lifetime reported in work (Table 4.5). The second component in [2], associated with a lifetime of the order of 2 ns, has been related to the presence of 1s2p $^3P_0$ and 1s2s $^3S_1$ levels. We note that, for the beam energy used in [2], the theoretical H- and Li-like charge state fractions are smaller than the He-like one (Table 4.1). In contrast, for the beam energies used in current study, the Li-like charge state fraction is higher than the He-like fraction. Further, although the H-like charge state fraction is very small, it nevertheless shows up in the spectrum (Fig. 4.4). H-like blending is more significant however at higher beam energies. Thus the presence of H-like M1 line and Li-like satellite line needs to be addressed in analysis of data. It is interesting to note that the 1s2p $^3P_2$ level lifetimes,
determined in [2] and in our study using different beam energies, experimental set-up and data analysis are nevertheless in good agreement.

The average value of apparent decay time \( \tau_c \) (131 + 8 ps, Table 4.4) lies between the theoretical lifetimes of the 2s \(^2\)S\(_{1/2}\) level in H-like Ni (215 ps) [22] and the 1s2s2p \(^4\)P\(_{5/2}\) level in Li-like Ni (43 ps) [17]. Further, the apparent decay time \( \tau_s \) in the single-foil experiment (85 ps, Table 4.4) is higher than the 1s2p \(^3\)P\(_{2}\) level lifetime. Those observations are consistent with blending in the 7.8 keV line arising from the H-like 2s \(^2\)S\(_{1/2}\) level. We have recently developed a set-up that enables us to perform the experiment for longer distances (up to a 100 mm travel). It is expected to disentangle the H-like 2s \(^2\)S\(_{1/2}\) contribution, thus allowing for the determination of the 2s \(^2\)S\(_{1/2}\) lifetime. A high resolution x-ray spectroscopy is being developed in our laboratory to confirm the existence of blending lines at 7.8 keV and their relative strengths and also to identify the unknown transition between 1.3 and 2.4 keV.

Table 4.1: Theoretical charge state fractions for the nickel beam as it leaves the foil (code ETACHA [30]. Foil thickness in \( \mu \)g/cm\(^2\). \( Q_{inc} \) the charge state of the incident beam.

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>( Q_{inc} )</th>
<th>Thickness ( \mu )g/cm(^2)</th>
<th>Charge state fraction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 340^a )</td>
<td>26</td>
<td>42</td>
<td>3.3</td>
</tr>
<tr>
<td>( 163^b )</td>
<td>12</td>
<td>45</td>
<td>0.05</td>
</tr>
<tr>
<td>( 160^b )</td>
<td>12</td>
<td>45</td>
<td>0.04</td>
</tr>
<tr>
<td>( 156^b )</td>
<td>12</td>
<td>45</td>
<td>0.04</td>
</tr>
</tbody>
</table>

\( ^a \) Dunford et al [6].

\( ^b \) This work.
Table 4.2: Theoretical (code ETACHA [30]) charge state fractions for a $^{35}$Cl+$^5$ beam (beam energy 56 MeV) and $^{35}$Cl+$^9$ beam (beam energy 88 MeV) emerging from a 20 $\mu$g/cm$^2$ carbon foil (as used in the experiment of Berry et al [31]). $F_n$ denotes the charge state fraction(%) for the nth ionic state.

<table>
<thead>
<tr>
<th>Energy</th>
<th>F11</th>
<th>F12</th>
<th>F13</th>
<th>F14</th>
<th>F15</th>
<th>F16</th>
<th>F17</th>
</tr>
</thead>
<tbody>
<tr>
<td>56 MeV</td>
<td>1.85</td>
<td>8.49</td>
<td>24.41</td>
<td>38.83</td>
<td>22.7</td>
<td>3.28</td>
<td>0.14</td>
</tr>
<tr>
<td>88 MeV</td>
<td>0.76</td>
<td>4.38</td>
<td>16.16</td>
<td>35.33</td>
<td>35.94</td>
<td>9.93</td>
<td>0.37</td>
</tr>
</tbody>
</table>

Table 4.3: Theoretical energies and lifetimes for the unresolved lines that may contribute to the 7.8 keV peak

<table>
<thead>
<tr>
<th>Ion</th>
<th>Line</th>
<th>Energy (keV)</th>
<th>Lifetime</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{58}$Ni$^{26+}$</td>
<td>$1s^2 \frac{3}{2}S - 1s2p^3P_2$</td>
<td>7.78[19]</td>
<td>70.6ps[16]</td>
</tr>
<tr>
<td>$^{58}$Ni$^{26+}$</td>
<td>$1s^2 \frac{3}{2}S - 1s2s^3S_1$</td>
<td>7.73[19]</td>
<td>2.3 ns[16]</td>
</tr>
<tr>
<td>$^{58}$Ni$^{24+}$</td>
<td>$1s^22s^2 \frac{3}{2}S - 1s2s2p^4P_{3/2}$</td>
<td>7.72[18]</td>
<td>43 ns[17]</td>
</tr>
<tr>
<td>$^{58}$Ni$^{27+}$</td>
<td>$1s^2 \frac{3}{2}S - 2s^2 \frac{3}{2}S_{1/2}$</td>
<td>8.07[23]</td>
<td>215 ps[22]</td>
</tr>
</tbody>
</table>

Table 4.4: Apparent decay times $\tau_s$ and $\tau_e$ in $^{59}$Ni. $\tau_s$ is associated with the H–like $2s \frac{3}{2}S_{1/2}$, and the He–like $1s2p^3P_2$, $1s2s^3S_1$ and $1s2s2p^4P_{3/2}$ levels. $\tau_e$ represents an effective contribution of all those levels except $1s2p^3P_2$, $\tau_s$ is obtained from one–exponent fit of the single–foil data and $\tau_e$ from two–exponent fit of the two–foil data (Eq. 4.4 fixing $\tau_1$ to $\tau_s$).

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>Peak energy (keV)</th>
<th>Lifetime (ps)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\tau_s$</td>
<td>$\tau_e$</td>
</tr>
<tr>
<td>163</td>
<td>7.78</td>
<td>130±12</td>
</tr>
<tr>
<td>160</td>
<td>7.78</td>
<td>118±6</td>
</tr>
<tr>
<td>156</td>
<td>7.78</td>
<td>146±13</td>
</tr>
<tr>
<td>Average lifetime</td>
<td>131±8</td>
<td>85±3</td>
</tr>
</tbody>
</table>
Table 4.5: Lifetime \( \tau_i \) for the 1s2p \(^3P_2\) level in He–like \(^{59}\)Ni and comparison with theoretical and experimental data. Single–foil data fitted with two exponents, see Eq.4.5 and text.

<table>
<thead>
<tr>
<th>Ion</th>
<th>Energy (mV)</th>
<th>Line Energy (keV)</th>
<th>Experiment This work</th>
<th>Experiment Other work</th>
<th>Theory</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ni(^{26})+</td>
<td>163</td>
<td>7.8</td>
<td>70±5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ni(^{26})+</td>
<td>160</td>
<td>7.8</td>
<td>67±6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ni(^{26})+</td>
<td>156</td>
<td>7.8</td>
<td>74±6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average lifetime</td>
<td></td>
<td></td>
<td>70.3±3</td>
<td>70±3[2]</td>
<td>70.6[16]</td>
</tr>
</tbody>
</table>

References


[29] EG &G ORTECH catalog/manual, Detectors and instruments for


