Chapter 2

Experimental set-up and methods

The experiments described in this thesis are performed with the apparatus called CHEOPS installed at the atomic physics facility of the KVI Groningen. The multicharged ions used in the experiments are produced with an ECR ion source. The initial energy of the ions is limited by the maximum voltage which the source can stand i.e. 20 kV. To obtain experimental data at higher energies we have used a compact post-accelerator to boost the energies of our He$^{2+}$ beams up to 75 keV/amu. With the multicharged ions various collision experiments are performed using different techniques. By means of photon emission spectroscopy we have studied collisions of He$^{2+}$ with He and H$_2$. From the spatial emission profiles we have deconvoluted the contributions of different spectroscopically unresolved transitions. The molecular dissociation of CO is studied with time-of-flight measurements using a reflectron ion mass spectrometer. We have developed a method to determine the kinetic energy released by dissociation.
2.1 Ion source and post-accelerator

Multicharged ions are produced with an Electron Cyclotron Resonance Ion Source (ECRIS) as described by Geller and Jacquot [15]. They are transported to the set-up using focusing and bending magnets. The schematic lay-out of the atomic physics facility is shown in figure 2.1. The ions extracted from the source form a continuous beam with an energy of \( q \times V_{ECR} \), with \( q \) the charge state of the projectile and \( V_{ECR} \) the extraction voltage of the source. The extraction voltage can be adjusted between 2 kV and 20 kV. The beam current for 8 kV He\(^{2+}\) and 8 kV O\(^{7+}\) is typically 80 \( \mu \)A and 4 \( \mu \)A, respectively, measured directly behind a 110° analysing magnet.

To obtain experimental data with He\(^{2+}\) projectiles at energies encompassing the 30 to 55 keV/amu injection energy of the He beams at JET we designed and built a compact post-accelerator to boost the energies of our beams (Dermaois et al. 1991 [16]). The radio frequency (RF) booster is basically a linear accelerator with two acceleration gaps. In front of it there is a double gap buncher. The gaps of the buncher are equipped with high-transmission grids, which define the gap widths and assure a homogeneous field in the gaps. The efficiency of the buncher, driven by a triangular RF voltage, is 40 to 45%. Upon entering the first gap of the accelerator the duration of the bunches is around 2 ns. The central acceleration electrode is powered via an RF transmission line wound like a spring and tuned to the frequency of the RF power supply, 13.56 MHz. For the highest beam energies reached, 75 keV/amu, the input power is 2 kW. The efficiency of the complete system, buncher and accelerator, to accelerate primary beams of 4.5 keV/amu He\(^{2+}\) ions is 30 to 35%. The beams are energy selected by a 45° bending magnet in front of the set-up. In combination with the diaphragms of the set-up the energy resolution is some 5%.

2.2 Photon emission spectroscopy

2.2.1 The apparatus

The apparatus for Photon Emission Spectroscopy (PES) is shown in figure 2.2. It has been described extensively by Hoekstra in his thesis [17]. Here the most important points will be discussed.

To collimate the ion beam, the ions enter the collision chamber through two diaphragms, which are 60 mm apart and have each a diameter of 3 mm. In the chamber the ions cross an atomic He beam or molecular H\(_2\) beam target which has a full width at half maximum of 4 mm. The gas effuses from a stainless steel capillary with a diameter of 1.5 mm and a length of almost 6 mm. Its position along and its distance to the ion beam can be changed without breaking the vacuum. The collision chamber is equipped with a liquid N\(_2\) trap, to which the capillary is connected. This reduces the background pressure and the temperature of the effusing gas and so increases the effective target beam density.

The target density is determined by measuring
the pressure in the gas supply tube with a capacitive manometer. The calibration of this value to the absolute target pressure is obtained by comparing a PES signal from the gas target with the one from a static target. Typically, the experiments are performed with a target density in the centre of the beam corresponding to an effective pressure of 30 mPa, while the residual background pressure was around 0.04 mPa. To assure the purity of the He target, the He was fed into the capillary through a molecular sieve.

The HeII transitions observed subsequent to the He$^{2+}$ + He collisions are indicated in figure 2.3. The HeII($n = 4 \rightarrow n = 3$) emission at 468.6 nm is observed perpendicular to the ion beam with a spectrometer for visible light. This spectrometer is equipped with an imaging system that allows us to scan along the ion beam. This scanning possibility is essential for determining the HeII($n = 4 \rightarrow n = 3$) cross sections accurately, because the lifetimes of the He$^+(4l)$ projectile states are so long that a considerable fraction of

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**Figure 2.1:** Schematic layout of the atomic physics facility.
Figure 2.2: Schematic view of the Photon Emission Spectroscopy set-up. A rotatable mirror allows us to scan the emission along the ion beam axis.
the states decays outside the observation length of the spectrometer. The spatial extent of the emission profiles can be exploited to determine the different HeII\( (4l \rightarrow 3l') \) transitions contributing to the HeII\( (n = 4 \rightarrow n = 3) \) line emission (see next section).

![Schematic representation of the HeII energy level scheme](image)

**Figure 2.3: Schematic representation of the HeII energy level scheme.** The relevant transitions are indicated together with their branching ratios. The measured transitions are indicated on the right side of the scheme together with their wavelengths in nm. Furthermore the lifetimes (in ns) of the 4\( l \) and 5\( g \) states are given above these levels.

The HeII\( (np \rightarrow 1s) \) Lyman transitions, having wavelengths in the range of 24.0 to 30.4 nm, can be measured with a grazing incidence VUV monochromator positioned under the double magic angle to avoid polarisation effects (Hoekstra et al. [18]). A position sensitive microchannel plate detector enables the simultaneous detection of all the HeII Lyman lines.

Both photon detection systems are calibrated absolutely on wavelength and sensitivity by means of calibrated lamps and various electronic and ionic collision processes with well known cross sections ([18,20] and references therein). Since the calibration is performed under the same experimental conditions as the measurements, all systematic errors in the absolute sensitivity and the target pressure cancel. Therefore, the absolute emission cross section, \( \sigma_{\text{em}}(\lambda) \), can be derived from the measured signal using:

\[
\sigma_{\text{em}}(\lambda) = C(\lambda) \times \frac{qS}{Qp} \tag{2.1}
\]

where \( q \) is the charge of the projectile, \( S \) is the measured signal, \( Q \) the accumulated ion charge in Coulomb and \( p \) the effective target pressure. \( C(\lambda) \) is the calibration constant including various conversion factors.

To assure that the magnetic field, which induces an electric field in the frame of the fast moving He ions, is so small that no Stark mixing of especially (quasi-) degenerate He\(^+\)(4\( l \)) states occurs we use two sets of Helmholtz coils by which the magnetic field inside the set-up is reduced to less than 10 \( \mu \)T. In this way the total electric field due to space charge effects and magnetic field is less than 0.5 Vcm\(^{-1} \), implying that no appreciable mixing of the He\(^+\)(4\( l \)) states will take place [18].
2.2.2 Spectroscopically unresolved lines

From the HeII energy level scheme shown in figure 2.3 it is clear that the different $4l \rightarrow 3l'$ transitions cannot be resolved spectroscopically. To extract the contributions of these transitions from the total HeII($n = 4 \rightarrow n = 3$) signals we exploit the fact that the lifetimes of the HeII($4l$) states are different and relatively long, i.e. in the ns range. The longer the lifetime the further the emission extends downstream from the atomic target along the ion beam. The spatial emission profile, $P_{4l}(z)$, of a specific $4l$ state is given by (Aumayr et al. 1984 [19], Hoekstra et al. [18,20]):

$$P_{4l}(z) = \frac{1}{\nu \tau_{4l}} \int_{z_0}^{z} T(z') \exp[-(z - z')/\nu \tau_{4l}] dz'$$  \hspace{1cm} (2.2)

where $\nu$ is the velocity of the ions, $\tau_{4l}$ the lifetime of the HeII($4l$) state, $z$ the position along the beam axis and $T(z)$ the target density profile. The centre of the target profile is chosen to be $z = 0$ and $z_0$ is the position of the last beam-collimating diaphragm in front of the target. The target density profile is determined on a regular basis by electron or proton impact excitation of non-resonant neutral He lines, especially the singlet HeI($4s \rightarrow 2p$) transition at 504.8 nm.

The measured spatial HeII($n = 4 \rightarrow n = 3$) signal, $S(z)$, is just equal to the sum of all the HeII($4 \rightarrow 3l'$) profiles weighted by their branching ratios, $\beta(4l \rightarrow 3l')$, and their cross sections, $\sigma(4l)$, and is thus given by:

$$S(z) = K \sum_{4l} \beta(4l \rightarrow 3) P_{4l}(z) \sigma(4l)$$  \hspace{1cm} (2.3)

with $K$ the absolute calibration constant. By measuring $S(z)$ at some 30 positions along the beam axis it is possible to extract the state selective HeII($4l'$) cross sections from the spatial emission profiles by a weighted least squares fit.

Figure 2.4: Spatial HeII($n=4 \rightarrow n=3$) emission profile for 40 keV/amu He$^{2+}$ ions colliding on He. The electron capture and the target-ion excitation contributions are indicated by the thin full and broken curves, respectively.

Figure 2.4 shows as an example the spatial HeII($n = 4 \rightarrow n = 3$) emission profile for
40 keV/amu He$^{2+}$ ions colliding with He. It presents the results of the deconvolution procedure for 40 keV/amu He$^{2+}+\text{He}$ collisions. The broken curve shows the target-ion excitation component and the thin full curve indicates the sum of the four electron capture contributions. It is clearly seen that the emission extends downstream from the atomic target along the ion beam. This is discussed in detail in chapter 3.

2.3 TOF measurements

2.3.1 The apparatus

A continuous beam of He$^{2+}$ or O$^{7+}$ ions is extracted from the ECR source. The extraction voltage of the source has been varied from 4 to 16 kV. With a chopper, which is installed in the beam line, the ion beam can be pulsed with a frequency of 25 kHz. The pulse width can be varied from 200 ns down to 15 ns. A schematic view of the setup is shown in figure 2.5. The ion beam enters the collision chamber through two collimating diaphragms, which are 60 mm apart and have each a diameter of 1 mm. In the setup the ions cross a gaseous CO molecular target from a grounded nozzle with an inner diameter of 0.9 mm and an outer diameter of 1.25 mm, which is cooled with liquid nitrogen. The distance of the nozzle to the ion beam can be changed without breaking the vacuum. In the experiments presented here it is positioned about 2.5 mm above the ion beam, leading to a Gaussian-like target profile with a full width at half maximum of 3.0 ± 0.5 mm. The target profile is measured using photon emission spectroscopy as described in section 2.2. The beam current is measured in a Faraday cup with a collimator in front.

The molecular ions and charged fragments, which are produced in charge changing collisions, are extracted perpendicular to the ion beam by two condenser plates at opposite voltages. The apertures in the condenser plates are covered with grids to ensure a homogeneous electric field. After passing a diaphragm, with a diameter which can be varied from 2 to 8 mm, the ions are accelerated into a so called reflectron time-of-flight spectrometer. The reflectron is discussed in more detail in the next section. Between the diaphragm and the reflectron there is a lens system of five electrostatic elements used for focusing. In the reflectron the ions travel in a field free region towards an electrostatic mirror in which they are reflected back into the field free region towards the detector, a set of two multichannel plates mounted in a chevron configuration. With appropriate adjustment of the voltages on the mirror apertures, time differences due to different starting positions in the extraction field are compensated regarding the total time-of-flight to second order [22]. This mirror technique together with a long drift length (800 mm) results in a high mass resolution. At the other side of the collision centre a channeltron is mounted for electron measurements. By adjusting a negative voltage on the entrance diaphragm and a positive voltage on the channeltron head, we can select electrons in a certain energy range.

We have performed different kinds of measurements. By using a pulsed beam, we have measured singles time-of-flight spectra with a Canberra (2048) time-to-amplitude converter (TAC). The beam is pulsed by a chopper which is placed
Figure 2.5: Schematic view of the apparatus for time-of-flight measurements.
Experimental set-up and methods

Figure 2.6: Scheme of the electronics used for a) time-of-flight and b) time-difference measurements.
in the beam line approximately 3 meters upstream from the collision centre. It consists of two parallel plates, one of them is put on a DC voltage of \( V_c/2 \) while at the other a square wave voltage is applied alternating between zero and \( V_c \), where \( V_c \) is typically around -300 V. At both \( V_c/2 \) crossings of the AC voltage the ions pass the diaphragms in front of the collision centre resulting in two beam pulses per chopper period. One flank of the applied AC voltage is steeper than the other, so the pulse lengths of the two beam pulses differ by a factor 10. Since we did not use a sweeper, the chopper period is adjusted to be at least twice the time-of-flight of the slowest particle produced in the collision. The chopper frequency is typically 25 kHz.

In figure 2.6a a scheme of the electronics is presented. The start of a time measurement is extracted from the blockpulse used as the chopper-driving signal. For this, the blockpulse is delayed for around 12 \( \mu \)s to partly compensate for the transit times of the projectile ions from the chopper to the collision centre and the time-of-flight of the fragments to the detector. We can select to trigger on the rising flank of the blockpulse, which corresponds to the shorter beam pulse (typically 20 ns). The signal from the multichannel plates used for ion detection is amplified and subsequently led into a constant fraction discriminator (CFD). The output of the CFD is connected to the stop channel of the TAC. The TAC output is led into a 100 MHz analog to digital converter (ADC) where the data are digitised and stored. The ADC can be read out by a personal computer.

In the spectra the time-of-flight determines the charge/mass ratio of the detected particle. In the TOF measurements the target pressure was about 8 mPa and the intensity of the chopped beam measured in the Faraday cup was in the order of 100 pA.

Coincidence spectra have been obtained, using a continuous beam, by starting the TAC on the first arriving fragment and using the signal from the other fragment as a stop. In this way time-difference spectra are measured. A scheme of the electronics is shown in figure 2.6b. To avoid that the TAC starts and stops at the same CFD output signal the start signal is delayed by some 50 ns. For a better signal to background ratio these measurements are performed with a very low target pressure of around 0.4 mPa and a beam intensity of about 100 pA. The total count rate was around 400 sec\(^{-1}\).

A second way of coincidence measurements can be obtained by using an electron, coming from ionisation processes during the collision, as a start signal. Then the TOF of both fragments from the same event can be detected. For multihit measurements a LeCroy 4208 unit is used. Unfortunately, up till now the statistics in these coincidence spectra are too low. For that reason only singles and time-difference spectra are discussed.

### 2.3.2 The reflectron

From the time measurements we deduce information on the kinetic energy of the fragments after dissociation (see the next section). Therefore, it is important that time differences due to different starting positions in the extraction field are...
Figure 2.7: Working of the reflectron. The shaded rectangles represent an ion packet which expands in the first drift stage due to different starting potentials, but shrinks in the second drift stage due to inversion in the electrostatic mirror. With an appropriate adjustment, the reflecting system provides second order space focusing regarding the total time-of-flight. Note that the drawing is not to scale. The dimensions are indicated at the bottom in mm.

Reduced. This can be done either by making the initial space distribution small compared to the distance between the extraction plates or by space focusing. To achieve space focusing together with a high mass resolution we have used a reflecting time-of-flight spectrometer or reflectron.

The design of the reflectron is based on the work of Karataev et al. (1972) and Mamyrin et al. (1973) and is described by van der Meij (1989) [21–23]. It provides second order space focusing regarding the total time-of-flight. A schematic drawing of the reflectron is shown in figure 2.7. Consider a packet of ions with given mass and no initial energy but produced at different starting positions in the extraction field, \( s - \Delta s \leq s \leq s + \Delta s \). At the end of the extraction region the ions within the packet will have different velocities due to the different starting potentials. Therefore, the packet expands during the flight through the spectrometer. However, after
the first drift stage the ions are reflected in an electrostatic mirror. The fastest ions penetrate deeper into the mirror and spend more time in there, so the slower ions leave the mirror before the faster ones. During the second drift stage the faster ions catch up with the slower ones. With an appropriate adjustment of the parameters of the reflecting system the length of the packet arriving at the detector can be minimised. Mamyrin et al. [22] have determined the relations the dimensions of the reflectron must satisfy. The voltages on the mirror apertures can be found by solving the following equations:

\[
\left( \frac{dT}{ds} \right)_s = 0 \quad \text{and} \quad \left( \frac{d^2T}{ds^2} \right)_s = 0 \quad (2.4)
\]

where \( T \) is the total time-of-flight and \( s \) the starting position.

During the experiments the reflectron settings are not only defined by the minimisation of the time spread but also by the maximisation of the count rate. The total count rate strongly depends on the voltages on five lens elements which are used to guide the ions through the wall of the collision chamber into the drift region of the reflectron. The optimal mirror voltages depend on the lens settings, and the count rate is dependent on the mirror voltages. So the optimisation is an iterative process.

For this optimisation process we implemented the calculations of the total time-of-flight in a spreadsheet program. With this program we can easily calculate the time-of-flight of a certain particle in all different parts of the detector system for all possible settings. Furthermore, the time difference between a particle started at \( s=0 \) and one started at \( s=\Delta s \) is shown [24]. In the experiments \( \Delta s \) is limited by the beam radius, around 0.5 mm.

### 2.3.3 Determination of kinetic energy release

Information on the kinetic energy release (KER) can be obtained by lowering the extraction voltage in the collision region. This is illustrated in figure 2.8. Consider two identical positive ions which are emitted along the detection axis with a certain initial velocity \( v_0 \), but in opposite directions.

**Figure 2.8**: Principle of the experimental technique. Two identical positive ions which are emitted along the detection axis in opposite directions will arrive at the detector with a time difference \( \Delta T \) proportional to the square root of the kinetic energy release. Energetic fragments which are expelled along the beam axis will be intercepted by the entrance diaphragm of the spectrometer.
The ion emitted towards the positive condenser plate will turn around due to the applied field. So after a time \( \Delta T \) it returns to its initial position. From then on its further time-of-flight and trajectory are identical to that of the ion initially emitted towards the spectrometer. Therefore, in the TOF spectrum these ions will exhibit a time difference equal to \( \Delta T \). For both fragments of a diatomic molecule which dissociates with a certain amount of kinetic energy release \( (U_{KER}) \), \( \Delta T \) is given by

\[
\Delta T = \frac{\sqrt{8\mu U_{KER}}}{qE}
\]  

(2.5)

where \( q \) is the charge state, \( E \) is the extraction field and \( \mu = m_1m_2/(m_1 + m_2) \) with \( m_1, m_2 \) the masses of the fragments.

Energetic fragments which are expelled along the beam axis will be intercepted by the entrance diaphragm of the spectrometer and will not be detected. This gives rise to a double peak structure in the TOF spectra for every fragment with sufficient kinetic energy compared to the product of extraction voltage and charge state. Using equation (2.5) we can for each individual fragment transform the time axis of our measured spectra to one of KER.

It may be clear that due to the blocking effect of the diaphragm the transmission of the spectrometer strongly depends on the kinetic energy of the charged particle and on the extraction voltage. So before analysing our data we have to correct for this energy dependent transmission.

The energy dependent correction functions have been calculated from the geometry of the extraction region for all different extraction fields.

Figure 2.9: a) Drawing of the situation at five successive times after the creation of an \( O^+ \) fragment with an initial energy of 5 eV in an extraction field of 50 V/cm. The spheres (drawn as circles) indicate all possible positions of this fragment at the different times. b) The situation at \( t_5 \) for a transmission of 20\%. The emitted ions on the sphere passing the diaphragm have the same initial energy but pass in a time interval \( \Delta t = x/v(t) \).
and diaphragm sizes used in the experiments. In figure 2.8a a sketch is drawn of the situation at five successive times after the creation of an $O^+$ fragment with an initial energy ($U_i$) of 5 eV in an extraction field ($E$) of 50 V/cm. The spheres (drawn as circles) indicate all possible positions of this fragment at the different times. Due to the initial velocity of the ion,
\[ v_o = \sqrt{\frac{2U_i}{m}} \]  
the sphere expands linearly in time. Due to the applied field ($E$) the centre of the sphere is accelerated towards the diaphragm with
\[ a = \frac{qE}{m} \]  

At a certain time, marked as $t_2$, the sphere of emitted ions is cut off by the diaphragm. The particles passing the diaphragm are assumed to be detected, leading to a peak in the TOF spectrum corresponding to the forward emitted ions. The transmission ($k$) of the ions can then be calculated as the ratio of the part of the surface inside the diaphragm (with radius $r_d$) and the total surface of the sphere.
\[ k = (1 - \cos \varphi) \]  
with
\[ \varphi = \arcsin \left( \frac{r_d}{v_o t_2} \right) \]  
The time $t_2$ can be calculated from equations (2.6) and (2.7) and the distance from the collision centre to the diaphragm, which is 10.5 mm. At time $t_4$ the backward emitted fragments pass the diaphragm. For these ions the radius of the sphere is larger, which results in a smaller transmission according to equations (2.8) and (2.9).

From the transmission functions we have deduced the energy dependent correction functions, $1/k$, which we have used for the correction of our spectra after transformation to energy scale. In figure 2.10 the correction functions for the charged oxygen fragments of CO are shown for an extraction field of 50 V/cm and a diaphragm of 2 mm.

**Figure 2.10:** Correction functions for $O^{q\pm}$ fragments for an extraction field of 50 V/cm and a diaphragm of 2 mm. In the inset it is shown that for all fragments with a KER above 2 eV the transmission is less than 10%.
Assumptions

In deriving these correction functions we have made some assumptions, which we will discuss now.

(i) We assumed an isotropic distribution of the emitted fragments. Although very little is known about the angular distribution of the emitted fragments after dissociation, it is known that there is a dependence of the cross sections for electron capture with respect to the orientation of the molecular axis. Since in general the dissociation time of a molecule is much shorter than its rotation time we can expect that the orientation of a molecular ion produced by electron capture is reflected in an anisotropic distribution of the fragments. At first sight an anisotropy doesn't influence our results because we have determined relative cross sections. But since we have determined the ratio of dissociation channels leading to different amounts of kinetic energy release, it might be possible that the anisotropy is not the same for all channels because different charge exchange processes are involved.

For an estimation of this effect in the energy range of our experiments we used theoretical and experimental results on the influence of the molecular orientation in H\(^+\) + H\(_2\) collisions. Experiments on this collision system were done by Yousif et al. (1988) [25]. They found no significant anisotropic angular distribution of pairs of H\(^+\) fragments formed by double ionisation or transfer-ionisation in H\(^+\) + H\(_2\) collisions in the energy range from 5 to 30 keV. However, the calculated transfer-ionisation cross sections of Fritsch et al. (1993) [26] are found to be sensitive to the polar angle \(\theta\) of the molecular axis at 4 keV but not at 10 keV. At 4 keV H\(^+\) emission at 90° is found to be 20% higher than the average emission.

Although these results can be different for CO, we estimate that in the energy range of 4 to 8 keV/amu the anisotropy effect in collisions with CO is less than 20%.

(ii) A well defined initial kinetic energy of a particle is assumed to contribute to a narrow time interval. This only holds when the radius of the sphere is large compared to the radius of the diaphragm. This can be seen in figure 2.9b. Here the situation is drawn comparable to figure 2.9a (t\(_2\)) for a transmission of 20%. The emitted ions on the sphere passing the diaphragm have the same initial energy but pass in a time interval \(\Delta t = x/v(t)\). If \(x \ll r_b\) this time interval is small relative to \(\Delta T\) (eq. 2.5). For \(x/r_b = 0.1\), \(\Delta t\) is about 10 ns which is an acceptable time spread. Since \(x/r_b\) is equal to the transmission factor \(k\) (eq. 2.8), \(x/r_b < 0.1\) holds when the correction factor is larger than 10. In figure 2.10 it is shown that for an extraction field of 50 V/cm and a diaphragm of 2 mm this is the case for all fragments if \(\text{KER} > 2\) eV.

(iii) All particles are assumed to be produced in a very small collision volume in the centre of the spectrometer viewing area. The collision volume in our experiment is defined by the beam diameter (1.0 mm) and the target width (FWHM = 3.0 mm). The electrostatic mirror in the reflection compensates for time differences which are caused by different starting positions in the x direction. However, time differences can also occur due to the fact that particles from different positions
in the y-z plane will follow different trajectories. Therefore, we now consider the area equal to the projection of the collision volume on the y-z plane.

For the coincidence measurements this area is limited by the observation region of the spectrometer since both fragments can only be detected if they are produced in this region. For the TOF measurements also fragments which are produced outside the spectrometer view can be detected if they are emitted with sufficient kinetic energy under a suitable angle. Such processes outside the observation region of the spectrometer should be recognisable by comparison of the spectra for the forward and backward emitted fragments, because the forward emitted particles are shifted to longer flight times while the backward emitted ions are shifted to shorter times. In section 5.3.2 it is shown that the shapes of the these spectra are more or less equal, indicating that decay outside the viewing area does not contribute significantly to the measured spectra.