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X-RAY INTENSITIES IN MUONIC NITROGEN

by

JOHN EDWARD DUCK

A thesis submitted to the Faculty of Graduate
Studies in partial fulfillment of the requirements for
the degree of Master of Science.

Department of Physics
Carleton University
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April, 1978

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ABSTRACT

Intensity measurements were made for several muonic atom x-ray transitions. These transitions occurred when negative muons were stopped in gaseous nitrogen at various pressures. The refilling times of the electronic states were determined using a muon cascade model and found to be in the order of 1.0×10^{-12} sec to 1.0×10^{-11} sec for N_2 pressures ranging from 4 atm to 0.5 atm.

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CHAPTER I

INTRODUCTION

The investigation of weak and electromagnetic interactions, their possible unification with the aid of gauge theories, and the existence of neutral currents, are all interrelated subjects confronting physicists today. The existence of neutral currents in high energy neutrino interactions has given support for the unification of the weak and electromagnetic interactions. Neutral current effects should also be observed in low energy phenomena and confirmation of their existence in atomic physics experiments would reinforce the unification theories. The presence of neutral currents could be detected by their parity violating effects which would be extremely noticeable in low Z muonic atoms, in particular, the $2S_{1/2} \rightarrow 1S_{1/2}$ transition, (Bernabeu et al., 1974 and Feinberg, G. and Chen, M.Y., 1974). More specifically, the neutral current parity violations would apparently enhance the forbidden M1 transition of the $2S_{1/2}$ state to the $1S_{1/2}$ state. Ordinarily, the principal mode of decay for the metastable $2S_{1/2}$ level to ground state, in low Z muonic atoms, is by two photon decay, with the probability of the one photon M1 transition being extremely small. Figure 1.1-1 shows these transitions. Neutral current parity violating effects, however, would cause a mixing of the $2S_{1/2}$ and the $2P_{1/2}$ states. This admixture causes the M1 transition to acquire an E1 component which produces an

FIGURE 1.1-1 Electromagnetic transitions involving
 $n = 1$ and $n = 2$ levels for low Z
 muonic atoms.

apparent enhancement of the M1 one photon decay.

The present experiment was a first generation experiment in which an attempt was made to observe the two photon decay of the $2S_{1/2}$ state for low Z muonic atoms. A previous search for the two photon decay of the $2S_{1/2}$ state had been attempted by Carter et al., 1977, using targets of Li, LiH, Be, BeH₂, B, B₁₀H₁₄ and LiBH₄, placed in the muon beam at the Space Radiation Effects Laboratory (S.R.E.L.). This coincidence experiment using two germanium detectors failed to observe the two photon decay, indicating a problem with refilling of the electronic states and the consequent depopulation of the muonic $2S_{1/2}$ state by means of radiationless transitions known as the Auger effect. To observe the two-photon transition, the Auger effect must be reduced so that the Auger transition rate is less than the two photon transition rate. This can be achieved by retarding the refilling of the electronic states and would be accomplished if the collision time of the target atoms is sufficiently lengthened. Our experiment, therefore, used gaseous targets of N₂, O₂ and B₂H₁₀ in order to reduce the collision rate. The use of gas targets and the addition of two more detectors in this experiment was a major improvement over the previous one. Four intrinsic germanium detectors were used to cover a larger solid angle around the target.

An important extension to the experiment is an analysis of the intensities of x-ray transitions produced by the cascade of the muon after it is captured in orbit around a target

nucleus. These intensities are extremely sensitive to refilling time and pressure of the target gas. Therefore, a study was made of the intensities of the muonic atom x-ray transitions for the N_2 target at three different pressures: 0.5 atm, 1 atm and 4 atm. Intensities were measured for the K and L series of N_2 at each pressure of the target gas. From these intensities, an estimate of the refilling time could be obtained and hence, the feasibility of observing the two photon decay using gas targets. Unfortunately, as the gas pressure is lowered to increase the refilling time, the capture rate of muons around target nuclei is reduced.

CHAPTER II

THEORY

2.1 - Muonic Atom Formation

A muonic atom is formed when a muon of negative charge is captured into an orbit around a target nucleus. This process takes several steps to occur, the first of which is the bombardment of a target material by a beam of negative muons. Before capture can take place, the high energy muon beam must be slowed down from kinetic energies of several MeV to velocities similar to the electron cloud of the target atoms.

The slowing down of the muons from several MeV to energies in the neighbourhood of 2 keV is achieved by passing the beam through condensed matter or degrader, and by ionization processes, the muons slow to the 2 keV energy region. This process takes approximately 10^{-10} sec and produces muons travelling in the target at velocities slightly larger than the velocities of the valence electrons of the target atoms. The velocity of the muons continues to decrease by collisions with atoms until they reach thermal velocities. This step takes another $10^{-13} - 10^{-14}$ sec. The muons are now capable of being captured into discrete orbits around the nuclei. In the special case of gaseous targets, this process takes $\sim 10^{-9}$ sec.

The capture process leads the muon into a state of high excitation, although the distribution of initial states is not well known. It is generally assumed for cascade calculations that

the muon is captured into an orbit whose distance from the nucleus is equal to that of the K shell electron. Therefore, the principal quantum number of the muon corresponding to the K shell electron ($n_e = 1$) can be shown as

$$n_\mu = (m_\mu/m_e)^{1/2} \approx 14$$

since the mass of the muon

$$m_\mu = 207 m_e$$

where m_e is the electron mass.

In summary, the muon is treated like a heavy electron and can be captured into a Bohr orbit around an atomic nucleus with principal quantum number

$$n_\mu \approx 14$$

The muonic atom thus formed, contains a nucleus of charge Z , $Z - 1$ electrons and a muon. Since the muon mass is approximately two hundred times larger than the electron mass, its Bohr orbits have radii (m_μ/m_e) times smaller than those of the electron. As previously shown, the $n = 14$ orbit of the muon corresponds to the $n = 1$ orbit of the electron. When the muon is captured and is populating the $n = 14$ muonic state, the lower energy states are all unoccupied so that the muon quickly cascades to the lower energy levels by means of Auger electron or electromagnetic

radiation emission. This cascade takes approximately 10^{-13} sec to occur. It will be noted that all the times involved such as capture time and cascade time, are much less than the mean lifetime of the muon which is 2.2×10^{-6} sec. Once the muon reaches ground state, it can decay by the following process:-

$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$

or it may be captured in the nucleus by the process:

$$\mu^- + p \rightarrow n + \nu_\mu$$

in a time of $10^{-7} \left(\frac{82}{Z}\right)^4$ sec.

2.2 - Muonic Cascade

Once the muonic atom has formed, we are dealing with a muon orbiting the nucleus in an (n, ℓ) state. Cascade calculations proceed from the $n = 14$ level with an initial distribution weighted for high ℓ states in the case of low Z muonic atoms (Y. Eisenberg and D. Kessler, 1961). The muon now cascades to lower energy levels by means of radiative or Auger transitions. The most significant radiative transitions would be of the electric dipole type for which $(n, \ell = n - 1) \rightarrow (n - 1, \ell - 1)$. These are the most probable transitions because of their high transition rates and lead the muon to circular orbits (i.e., $\ell = n - 1$). Also possible are transitions of the kind

$(n, \ell = n - 2) \rightarrow (n - 1, \ell)$, but their transition rates are generally smaller than the $(n, n-1) \rightarrow (n - 1, n - 2)$ transition.

As mentioned, the two methods by which the muonic atom can deexcite are by a radiative transition or emission of an Auger electron. In the first case, a photon is emitted from the atom when the muon jumps to a lower energy state, whose orbital quantum number ℓ changes by one. For a radiative transition, the selection rule requires $\Delta\ell = \pm 1$.

The second mode of deexcitation is by the simultaneous ejection of an electron from the electron cloud surrounding the muonic atom when the muon cascades to a lower energy level. This radiationless transition, called the Auger Effect, competes with radiative transitions as a means of lowering the energy level of an excited atom, so that an electron is emitted rather than a photon.

In a paper by G.R. Burbidge and A.H. de Borde (1953), on the mesonic Auger effect, expressions for the radiative and Auger transition rates were calculated. From these expressions, it is seen that the radiative transition rate varies as Z^4 while the Auger transition rate is almost independent of Z . These probabilities can also be expressed in terms of the transition energy ΔE . The probability for a radiative transition is

$$P_R \propto (\Delta E)^3$$

while the probability for Auger deexcitation becomes

$$P_A \sim (\Delta E)^{-1/2}$$

From the above relations it is seen that Auger transitions are important in muon jumps between states of small ΔE , while radiative transitions will dominate for jumps with large ΔE . Auger and radiative rates for different elements have been calculated by E.H.S. Burhop (1952) and are listed in Table 2.2-1.

As stated previously, transitions of the $(n, n-1) \rightarrow (n-1, n-2)$ type predominate over the $(n, n-2) \rightarrow (n-1, n-2)$ type, except in the $2S \rightarrow 1S$ transition. A muonic atom in the $2S$ state can drop to the $1S$ state by Auger emission, or jump to the $2P$ level by a radiative transition, if the $2P$ level is below the $2S$ level. For the particular case of $Z = 5$, the Auger rate for the $2S \rightarrow 1S$ jump is 5.2×10^9 transitions/sec while the radiative $2S \rightarrow 2P$ transition rate is 2.4×10^4 transitions/sec. The small radiative rate is because of the small ΔE value of the $2S \rightarrow 2P$ jump. As discussed in Chapter I, the $2S \rightarrow 1S$ radiative transition may occur via a two-photon $E1$ or an extremely hindered one photon $M1$ transition. It is, therefore, obvious that the Auger rate for the $2S \rightarrow 1S$ transition is a competing part of the deexcitation of the $2S$ level in low Z muonic atoms.

The initial cascade of the muon through the higher energy levels causes a strong Auger effect since the (ΔE) of these levels is small. By the time the muon reaches the lower

Table 2.2-1 Transition rates for μ^- -mesons inside the K-electron orbits

Quantum numbers of initial and final states $n, l \rightarrow n', l'$	Type of transition	Atomic number Z				
		3	5	10	20	40
15, 14 $\rightarrow$ 14, 13	Radiative	5.20×10^8	2.03×10^9	3.35×10^{10}	5.2×10^{11}	8.32×10^{11}
10, 9 $\rightarrow$ 9, 8	Radiative	4.08×10^8	1.60×10^{10}	2.56×10^{11}	4.1×10^{12}	6.55×10^{12}
9, 8 $\rightarrow$ 8, 7	Radiative	7.00×10^8	2.74×10^{10}	4.40×10^{11}	7.0×10^{12}	1.13×10^{13}
8, 7 $\rightarrow$ 7, 6	Radiative	1.28×10^9	5.00×10^{10}	8.00×10^{11}	1.3×10^{13}	2.05×10^{13}
7, 6 $\rightarrow$ 6, 5	Radiative	2.55×10^9	9.96×10^{10}	1.60×10^{12}	2.6×10^{13}	4.10×10^{13}
7, 6 $\rightarrow$ 6, 5	Auger	—	—	3.5×10^{11}	7.0×10^{12}	8.0×10^{12}
6, 5 $\rightarrow$ 5, 4	Radiative	5.68×10^9	2.21×10^{11}	3.54×10^{12}	5.7×10^{13}	9.06×10^{13}
6, 5 $\rightarrow$ 5, 4	Auger	—	—	3×10^{11}	4.0×10^{12}	4.1×10^{12}
5, 4 $\rightarrow$ 4, 3	Radiative	1.47×10^{10}	5.72×10^{11}	9.16×10^{12}	1.5×10^{14}	2.3×10^{14}
5, 4 $\rightarrow$ 4, 3	Auger	—	—	1.6×10^{12}	1.7×10^{13}	1.8×10^{13}
4, 3 $\rightarrow$ 3, 2	Radiative	4.76×10^{10}	1.86×10^{12}	3×10^{13}	4.8×10^{14}	7.6×10^{14}
4, 3 $\rightarrow$ 3, 2	Auger	1.0×10^{11}	4.0×10^{12}	5.0×10^{13}	5.4×10^{14}	5.5×10^{14}
3, 2 $\rightarrow$ 2, 1	Radiative	2.23×10^{11}	8.68×10^{13}	1.4×10^{14}	2.35×10^{15}	3.6×10^{15}
3, 2 $\rightarrow$ 2, 1	Auger	—	6.0×10^{12}	—	9.0×10^{13}	9.1×10^{13}
2, 1 $\rightarrow$ 1, 0	Radiative	2.16×10^{11}	8.44×10^{13}	1.35×10^{14}	2.15×10^{15}	3.5×10^{15}
2, 1 $\rightarrow$ 1, 0	Auger	—	2.1×10^{11}	2.8×10^{11}	3.1×10^{11}	3.2×10^{11}
2, 0 $\rightarrow$ 2, 1	Radiative	—	2.4×10^{11}	2.3×10^{11}	1.4×10^{12}	2×10^{12}
2, 0 $\rightarrow$ 2, 1	Auger*	—	5.2×10^9	5.2×10^9	5.2×10^9	5.2×10^9
2, 0 $\rightarrow$ 1, 0	Internal pairs	—	—	—	—	—
8, 6 $\rightarrow$ 6, 5	Radiative	—	2.9×10^{10}	4.68×10^{11}	7.5×10^{12}	1.2×10^{13}
8, 3 $\rightarrow$ 3, 2	Radiative	—	2.03×10^{11}	3.25×10^{12}	5.2×10^{13}	8.3×10^{13}
8, 1 $\rightarrow$ 1, 0	Radiative	—	1.11×10^{11}	1.79×10^{12}	2.9×10^{13}	4.6×10^{13}
15, 13 $\rightarrow$ 13, 12	Radiative	—	3.42×10^9	5.47×10^9	8.8×10^9	1.4×10^{10}
15, 7 $\rightarrow$ 7, 6	Radiative	—	6.37×10^9	1.02×10^{10}	1.6×10^{11}	2.6×10^{11}
15, 1 $\rightarrow$ 1, 0	Radiative	—	1.67×10^{11}	2.68×10^{12}	4.3×10^{13}	6.9×10^{13}

* The abnormally low values for this transition, calculated by Wheeler, arose from the existence of a node in the 2s wave function causing very considerable cancellation in the transition matrix element.

energy states, the muonic atom should be stripped of its electron cloud. This would increase the chance of observing a two-photon emission for the $2S \rightarrow 1S$ jump, since Auger emission would be impossible with no electrons filling the electronic shells. However, during the time the muon cascades down to the lower levels and rids the atom of its electrons by the Auger effect, collisions can occur with other atoms whose electron shells are filled. This process causes a reconstruction of the electron cloud around the atom and therefore, creating the problem of a non-negligible Auger transition rate for the $2S$ state. Because of the Auger competition, the intensity of the x rays emitted from the atom during muon cascade is extremely sensitive to the refilling time of the electronic shells.

One method of altering this refilling time is by changing the pressure of the target gas. As the pressure of the gas decreases, the number of collision per unit time between the atoms is also reduced, thereby, lengthening the time for refilling of the electronic shells.

Measuring the intensities of the x rays emitted via radiative transitions during the muonic cascade will be a study of the refilling time.

2.3 - Cascade Calculation by Computer

A cascade program has been developed using calculations suggested by Eisenberg and Kessler (1961). This program,

written by J. Hufner of the University of Heidelberg, determines Auger and radiative transition rates for muonic atoms and can be used to calculate the expected intensity ratios of K and L series x rays. To begin the calculations, the program assumes all muons populate the state with principal quantum number $n = 14$. This creates a system with the muon inside the electron cloud of the atom and, therefore, is treated as a heavy electron orbiting a nucleus of charge $+Ze$. The initial distribution of muons for different ℓ values of the $n = 14$ level is set by the programmer. It has been determined by comparison with experiment that a statistical distribution weighted towards states of high angular momentum gives the best results for low Z atoms. This initial distribution is proportional to $(2\ell + 1)e^{a\ell}$, where "a" is an adjustable parameter. For low Z elements, this distribution with a value of $a = 0.2$ produces best agreement with experimental data. (Eisenberg and Kessler, 1961)

During the initial cascade of the muon through the higher energy levels, the atom is stripped of its electron cloud by Auger transitions. Interactions with other atoms whose electronic states are populated causes a refilling of the emptied shells. The time taken for this refilling process to occur has a large effect on the final x-ray intensities calculated by the program. A refilling time parameter is therefore, entered into the program to represent the time taken for reconstruction of the K and L electronic shells. Starting

from these conditions, the program then calculates populations of each state as the cascade proceeds towards ground state. The intensity and energy of each transition is determined by the program and a theoretical spectrum of the muonic cascade produced.

CHAPTER III

EXPERIMENTAL METHOD

3.1 - The Muon Beam

Muonic atoms are formed when a target material is bombarded by a negative muon beam. In the present 2S search experiment, the muon beam was produced by the 600 MeV proton synchrocyclotron of the Space Radiation Effects Laboratory located in Newport News, Virginia. The high energy protons produced by the accelerator are directed towards a target so that the reaction

$$p + \pi^- \rightarrow p + p + \pi^-$$

can occur. The negative pions produced in this reaction are channeled into a π^- beam. This beam has a flux of approximately 750,000 π^- per sec. with a momentum of 200 MeV/c at SREL. The pions then decay via the reaction

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu \quad \text{with } \tau \approx 0.046 \mu\text{s} \quad (\text{in lab frame})$$

The muons now produced come off the pion beam in either the forward or backward momentum direction, as compared to the pion rest frame. In the present experiment, the lower energy backward momentum muon beam was utilized. The use of a bending magnet separated out these 100 MeV/c momentum muons and directed them towards the target area. The muons were also produced in

bursts which lasted 10 ms.

3.2 - The Target Area

Muons of several MeV were sent to the target area shown in Figure 3.2-1. The target area consisted of four parts: the aluminum box containing the target gas, the muon telescope array, the four intrinsic germanium detectors and the degrading material used to slow down the muons.

Since the targets for this experiment were gaseous, an aluminum box was constructed to contain these gases. This box was built by our collaborators in the experiment, the College of William and Mary Physics Department in Virginia. The aluminum box (see Figure 3.2-1) was designed so that the air could be pumped out and one of the target gases drawn in, maintaining the desired pressure. The range of gas pressures used during the experiment was from 1/2 atm to 4 atm.

Located on the top, bottom and two sides of the target box were holes which allowed four intrinsic germanium detectors to surround a small volume of the target gas (see Figure 3.2-2). If one assumes a point source in the center of the target, the percentage of solid angle covered by each detector can be estimated using the approximate relation

$$\Omega_i = A_i / 4\pi r_i^2$$

where

FIGURE 3.2-1 Side view of target area.

FIGURE 3.2-2 Back view of target area with orientation of intrinsic germanium detectors.

Ω_i is the solid angle covered by the i^{th} detector as a fraction of the total solid angle 4π steradians.

A_i is the surface area of the i^{th} detector

r_i is the distance from the center of the target to the surface of the i^{th} detector.

Table 3.2-1 Detector Solid Angle Calculation

<u>Detector</u>	<u>r_i</u> <u>cm</u>	<u>A_i</u> <u>cm²</u>	<u>$4\pi r_i^2$</u> <u>cm²</u>	<u>Ω_i (x 100)</u>
1	6.35	20	506.7	3.95%
2	6.35	20	506.7	3.95%
3	5.08	10	324.3	3.08%
4	5.08	10	324.3	3.08%

3.3 - Germanium Detectors

Four intrinsic germanium detectors were used. Two of these detectors had surface areas of 20 cm² and were referred to as detector 1 and detector 2, (see Table 3.2-1). These detectors had an intrinsic germanium diode and were manufactured by Aptex/NRD of Canada. In front of the diode was a beryllium window of thickness .055 cm. Two smaller detectors referred to as detector 3 and detector 4 were also employed in the detection of the muonic x-rays. These detectors were manufactured by

Princeton Gamma-Tech (PGT) and had surface areas of 10 cm^2 with beryllium windows of .035 cm thickness.

The resolutions of these detectors were as follows. Detector 1 had a resolution of 930 eV at 122 keV and 898 eV at 59.5 keV. The resolution of detector 2 was 1044 eV at 122 keV. The resolution of the smaller detectors was 844 eV at 122 keV for detector 3 and 626 eV at 122 keV for detector 4. Since detector 4 had the best resolution and a solid angle coverage comparable to the other detectors, the x-ray intensity measurements were performed using data collected by this detector.

3.4 - Muon Telescope

When the muons reached the target area, they then travelled through two plastic scintillation counters S_1 and S_2 (see Figure 3.2-1). The beam was then slowed down by a degrader D which consisted of 3.81 cm of CH_2 and .76 cm of teflon. The amount of this degrader was varied so that the maximum number of muons would stop in the target gas. The slowed muons then passed through a third scintillator S_3 before reaching the aluminum box containing the gas. Entering the box, the muons passed through its 0.159 cm aluminum window as well as another 1.91 cm of beryllium degrader, before reaching scintillation counters S_4 , S_{5A} , S_{5B} and the target gas between the germanium detectors. If the muons were not stopped at this point, they would pass through scintillators V_1 and V_2 .

The plastic scintillators $S_1, S_2, S_3, S_4, S_{5A}, S_{5B}, V_1$ and V_2 were connected by light pipes to RCA 8575 photomultiplier tubes. Signals from these photomultiplier tubes were used to determine the number of muons actually stopping in the target area. A coincidence of S_1, S_2, S_3 , and S_4 signals and not V_1 or V_2 meant that a muon was captured by the target. If a signal was received from the veto counters V_1, V_2 , it indicated the muon passed through the target without being captured. Coincidence signals from S_1, S_2, S_3 and either of S_{5A} and S_{5B} also indicated a bad event, since the muons would not be captured between the germanium detectors.

3.5 - Logic

The telescope logic used to define the muon beam and the Ge logic which indicated photons striking the germanium detectors are shown in Figure 3.5-1 and 3.5-2 respectively. The combined logic system defined good events and the detector which recorded the event. In Figure 3.5-1, a STOP event indicated that a muon had passed through scintillators S_1, S_2, S_3 and S_4 and not through S_{5A}, S_{5B}, V_1 or V_2 . Therefore, $S_1 \cdot S_2 \cdot S_3 \cdot S_4 \cdot \overline{VETO}$ indicated a muon had been stopped in the target.

$$STOP = S_1 \cdot S_2 \cdot S_3 \cdot S_4 \cdot \overline{VETO}$$

A VETO signal was produced by a muon passing through any of the scintillators S_{5A}, S_{5B}, V_1 or V_2 . In this experiment, the number of muon stops per second was ~3000. Figure 3.5-2 shows the Ge logic. If anyone of the four germanium detectors

FIGURE 3.5-2 The Ge Logic

fired, a Ge signal was produced.

A valid event was defined by a STOP-Ge signal. For this signal to occur, a coincidence was required between the STOP pulse and the Ge pulse. The computer received an interrupt when a STOP-Ge signal was produced indicating a valid event.

Pileup protection was incorporated into the muon telescope logic (see Figure 3.5-1), and was supplied for the Ge logic by the EG & G GP100 Pile-up gate (see Figure 3.5-2).

A LRS Dual Gate Generator 222 was also used in the logic (Busy F/F) to indicate that the computer was ready, and could accept the event for processing. This was reset when the computer was ready for the next valid event.

The STOP-Ge signal was used as a start pulse for the LRS TDC 2228 with the stop pulse supplied by a delayed germanium detector signal. Each detector had its own input into the TDC and, therefore, timing information was obtained for individual detectors. A STOP-Ge pulse was also sent to the C212 EG & G coincidence buffer, which was strobed by the computer. Since the C212 coincidence buffer received signals from each detector into separate inputs, the individual detectors which fired in coincidence with a stopped muon, were recorded.

Amplified signals from the Ge detectors were sent to the EG & G AD811 ADC which digitized the signals and enabled the computer to process the data for energy information.

Signals from the preamplifier of detectors Ge1 and Ge2 were

amplified by the ORTEC 450 amplifier while those from Ge3 were amplified by the TENNELEC TC 203BLR linear amplifier. Ge4 preamplifier signals were amplified by the TENNELEC TC205 linear amplifier. The gain and zero positions of the AD811 ADC were stable throughout the experiment.

3.6 - On-Line Computer

The Data General Nova 820 computer was used during the experiment. Its memory is 32K of 16-bit words. Additional memory of 64K 18-bit words was also used for data only. The system also included two 1.25 megaword disk drives, a nine track 800 BPI tape drive, a Tektronix Storage Display Unit, an Infoton Video Display Terminal, a Teletype ASR33, a Centronics 501 Line Printer and a Calcomp 565 Incremental Plotter.

When a valid event occurred, the computer was sent an interrupt. The computer then read the data from the C212 coincidence buffer, the AD811 ADC and the 2228 TDC. The processing time per interrupt was approximately 420 μ s and the number of interrupts per second was approximately 200. After the computer had processed an interrupt, a signal was sent to the logic allowing the next event to be processed.

After the events had been processed, they were eventually dumped into the appropriate histograms which were stored on disk. These histograms were finally dumped on

magnetic tape for future analysis. Raw data which included energy, timing, pile-up and detector information were also stored on magnetic tape.

3.7 - Data Acquisition

A run consisted of data collected for a particular gas target and pressure over a typical period of four to eight hours in length. The pressure was then changed and another run started. Runs were made with targets of N_2 , O_2 and B_2H_{10} at pressures of 1/2 atm, 1 atm and 4 atm.

Signals sent from the muon telescope logic (Figure 3.5-1) and from the Ge logic (Figure 3.5-2) to the 2228 TDC supplied timing information for each detector. This enabled the x-ray energy data to be stored in three spectra: early prompt and delayed. Delayed events could be caused by muon capture in the nucleus and subsequent photon emission. The majority of data which were caused by muonic cascade appeared in the prompt spectra.

A total of twenty-three spectra were accumulated and stored on disk. Doubles spectra which summed prompt energy data from two detectors were also collected. Table 3.7-1 lists these spectra.

Table 3.7-1 Spectra Stored on Disk by Computer

<u>Spectrum Number</u>	<u>Description of Spectrum</u>
0	Energy (early) detector 1
1	Energy (prompt) detector 1
2	Energy (delayed) detector 1
3	Timing detector 1
4	Energy (early) detector 2
5	Energy (prompt) detector 2
6	Energy (delayed) detector 2
7	Timing detector 2
8	Energy (early) detector 3
9	Energy (prompt) detector 3
10	Energy (delayed) detector 3
11	Timing detector 3
12	Energy (early) detector 4
13	Energy (prompt) detector 4
14	Energy (delayed) detector 4
15	Timing detector 4
16	DOUBLES $E_1 + E_2$
17	DOUBLES $E_1 + E_3$
18	DOUBLES $E_1 + E_4$
19	DOUBLES $E_2 + E_3$
20	DOUBLES $E_2 + E_4$
21	DOUBLES $E_3 + E_4$
22	MULTIPLE $E_n + E_m$ ($n < m$)

CHAPTER IV

ANALYTICAL METHOD

4.1 - General

The K and L series (see Figure 4.1-1) of the N_2 target were analysed using the prompt energy spectra (SP13) collected by detector 4 (Ge4). This detector was chosen for the analysis because of its superior resolution, as compared with the other germanium detectors (see section 3.3).

The nitrogen data were summed into three pressure groups. Nitrogen runs at a pressure of 4 atm formed one group, while runs at 0.5 atm and runs at 1 atm formed the other two groups of data. Table 4.1-1 lists these summed runs, their computer disk file name, the total running time, the number of muons stopped and several other run statistics.

Individual runs were summed only if the peak position and full width at half maximum of each peak were the same.

4.2 - Calibration

Prompt energy spectra from Ge4 (SP13) were used for energy calibration of the data. Present in these spectra were several intense muonic x-ray transitions whose energies are well known. Table 4.2-1 lists these calibration peaks and their energies. Centroids were determined for each peak from SP13 and the data fitted by linear regression to the expression,

$$E = sC_E + E_0$$

FIGURE 4.1-1 Muonic Atom K and L Series

Radiative Transitions

* n is the principal quantum number

Series line	Quantum numbers of initial and final state $(n, \ell) \rightarrow (n', \ell')^\dagger$
K_α	$(2, 1) \rightarrow (1, 0)$
K_β	$(3, 1) \rightarrow (1, 0)$
K_γ	$(4, 1) \rightarrow (1, 0)$
K_δ	$(5, 1) \rightarrow (1, 0)$
K_ϵ	$(6, 1) \rightarrow (1, 0)$
L_α	$(3, \ell) \rightarrow (2, \ell')$
L_β	$(4, \ell) \rightarrow (2, \ell')$
L_γ	$(5, \ell) \rightarrow (2, \ell')$
L_δ	$(6, \ell) \rightarrow (2, \ell')$
L_ϵ	$(7, \ell) \rightarrow (2, \ell')$

† where
 $\Delta \ell = (\ell - \ell')$
 $= \pm 1$

Table 4.1-1

Pressure	Disk File Name	Total Run Time	STOP (counts)	STOP-Ge (counts)	Ge4 (counts)
4 atm	N245PSI.SS [†]	2.1×10^5 sec.	6.5×10^8	4.6×10^7	2.0×10^9
1 atm	N2ATMA.SS [*]	2.8×10^4 sec.	6.3×10^7	4.7×10^6	2.8×10^8
1 atm	N2ATMB.SS [*]	4.2×10^4 sec.	9.6×10^7	7.1×10^6	3.2×10^8
0.5 atm	N28151N.SS [†]	1.3×10^5 sec.	3.7×10^8	3.1×10^7	6.7×10^8

* N2ATMA summed runs 2 and 3, while N2ATMB summed runs 2, 3, and 11. The threshold level of Ge4 was set at 33 keV for run 11, therefore, N2ATMA.SS was used to analyse the L-series and N2ATMB.SS was used to analyse the K-series.

† Several pressure systems were used during the experiment 4 atm was referred to as 45 p.s.i. and 0.5 atm referred to as - 15 inches of Hg.

where

E is the energy in keV

S is the ADC gain in keV per channel

C_E is the channel number of the peak centroid

and

E_0 is the energy of channel zero in keV

Table 4.2-2 lists the results of the calibration for each pressure run. The actual energy values were compared to the values calculated by the linear regression fit, with ΔE being no larger than $\pm .05$ keV where $\Delta E = \text{calculated energy} - \text{actual energy}$.

4.3 - Peak Fitting Program

The data were analysed using a fortran IV computer program (Wadden, 1977) on the NOVA 820 computer. The program was able to fit up to five peaks in a two hundred channel range, supplying information on the centroid, full width at half maximum and intensity of each peak.

Basically, the program fits the data with a Gaussian distribution on a quadratic background. Several peaks, however, required special treatment, such as the addition of exponential tails on the upper or lower end of the gaussian. The program allowed for this as well as a term which fits a step in the background. Figure 4.3-1 displays a peak which needed these

Table 4.2-1 Calibration Sources

<u>Source</u>	<u>Energy (keV)*</u>
$^{12}\text{C}_{\text{L}\alpha}$ (3d - 2p)	13.966
$^{12}\text{C}_{\text{K}\alpha}$ (2p - 1s)	75.248
$^{12}\text{C}_{\text{K}\gamma}$ (4p - 1s)	94.095
$^{14}\text{N}_{\text{K}\alpha}$ (2p - 1s)	102.406
$^{16}\text{O}_{\text{K}\alpha}$ (2p - 1s)	133.525
$^{16}\text{O}_{\text{K}\beta}$ (3p - 1s)	158.408

* Reference: R. Engfer et al., 1974

Table 4.2-2 Calibration Factors of
SP13 for each Pressure Run.

<u>Pressure</u>	<u>S(keV/ch)</u>	<u>E₀(keV)</u>
4 atm	.1001	-.035
1 atm	.1001	.010
0.5 atm	.1001	-.045

additional features.

The mathematical function used to fit the peaks has the form:

$$F(x) = B(x) + \sum_{i=1}^5 [G_i(x) + E_i(x) + S_i]$$

where i sums over one to five peaks being fitted. $B(x)$ represents the background term.

$$B(x) = B_0 x^2 + B_1 x + B_2$$

$G_i(x)$ is the gaussian distribution for the i^{th} peak.

$$G_i(x) = \frac{I_i}{\sigma_i \sqrt{2\pi}} e^{-(x - \bar{x})^2 / 2\sigma_i^2}$$

where

I_i is the intensity of the i^{th} peak,

$\bar{x}$ the peak's centroid

and

σ_i is the standard deviation of the Gaussian.

$E_i(x)$ is the exponential tail added to the Gaussian of the i^{th} peak.

ATMB C K ALPHA
SPECTRUM NO. 13
FIT RANGE = 735 769
PEAKS FITTED = 1
STAT ERROR ON PEAK 1 = 0.0138 (EV)
CHI/F = 0.8688 DEG. OF FREE. = 24

S/N(1) = 2.8093
SIG = 40842.2700 NOISE = 14538

1	982.7869	+-	6.5951
2	-10.1747	+-	0.2888
3	-0.1122	+-	0.0097
4	41030.2700	+-	315.0654
5	752.4177	+-	0.0244
6	6.5886	+-	0.0478
11	-0.0190	+-	0.0007
12	0.0097	+-	0.0008
13	748.0000	+-	0.0000
14	-0.4504	+-	0.0227

Figure 4.3-1 A Typical Histogram
Including Computer
Fitting Parameters.

$$E_i(x) = I_i f_i^u e^{-\lambda_i^u (x - c_i^u)} \cdot [1 - 1/((x - c_i^u)^2 + 1)], \text{ for } x > c_i^u.$$

The above expression would add an exponential tail to the upper end of the gaussian. The following function would add an exponential tail to the lower end of the gaussian.

$$E_i(x) = I_i f_i^l e^{-\lambda_i^l (c_i^l - x)} \cdot [1 - 1/((x - c_i^l)^2 + 1)], \text{ for } x < c_i^l.$$

The parameters involved in these expressions are:

f_i^u, f_i^l - the fractional intensities of the upper and lower exponentials in terms of the gaussian intensity I_i .

λ_i^u, λ_i^l - the decay constants of the exponentials
and

c_i^u, c_i^l - the cut off channels for the upper and lower exponential tails.

Between these cut off channels, the value of the exponential term $E_i(x)$ is zero.

$$E_i(x) = 0 \text{ for } c_i^l < x < c_i^u.$$

The expressions also include a term which provides a smooth and continuous summation at the cut off points.

The final term S_i , produces a step in the background and has the form:

$$S_i/100 \sum_{x'=0}^x (G_i(x') + E_i(x'))$$

The size of this term is proportional to the area under the peak. The parameter s_i determines whether the step is up or down. If s_i is negative, the background step would be down, while a positive value of s_i causes an upward step in the background.

The fitting program used a minimization of χ^2 procedure to determine the most accurate values of the parameters. The program was run for thirty to fifty cycles, until the value of χ^2 would not improve. At this point, a print out was made of the parameters and the value of χ^2/F where F is the number of degrees of freedom. A value of χ^2/F less than 2.0 was considered acceptable. An error on each parameter was also computed. This error was the increment required to change the value of χ^2 by one.

The program had the ability of fixing the value of certain parameters by setting the increment to zero. This procedure was useful for background subtraction, when a second peak was buried beneath a K or L series peak.

A typical program output can be seen in Figure 4.3-1. Parameters 1, 2 and 3 list the values of B_2 , B_1 and B_0 respectively for the background term. The intensity of the peak, its centroid and full width at half maximum are parameters 4, 5 and 6. The fractional intensity, decay constant and cut off

channel number for a lower exponential tail are parameters 11, 12 and 13, while parameter 14 is the step in background parameter.

CHAPTER V

MUONIC ATOM X-RAY ANALYSIS I

5.1 - General

Analysis of the muonic atom x-ray spectra consisted of fitting the peaks by means of the program described in Chapter IV and obtaining their intensities. The analysis was carried out in two steps:

I) intensity measurements of K series transitions for each pressure of the nitrogen target,

II) intensity measurements of L series transitions for the three pressure groups of nitrogen data

This chapter contains analysis of the K series transitions of nitrogen gas at 0.5 atm, 1 atm and 4 atm (see Figures 5.1-1 to 5.1-3). Table 5.1-1 lists these transitions and their energies. The errors attached to the intensity measurements are calculated by the fitting program, and include the statistical error and the fitting error which would change χ^2 by 1. The intensity calculations which follow do not include corrections for the interfering background. The background subtraction techniques used to calculate the final intensities will be discussed at the end of the chapter.

N₂ 4 ATM K SERIES

SQRT PLOT

SPECTRUM NO. 13

Figure 5.1-1 K Series of N₂ at 4 atm

N2 1 ATM K SERIES

SQRT PLOT

SPECTRUM NO. 13

Figure 5.1-2 • K Series of N_2 at 1 atm

N₂ 0.5 ATM-K SERIES

SQRT PLOT

SPECTRUM NO. 13

Figure 5.1-3 K Series of N₂ at 0.5 atm.

Table 5.1-1 K Series Energies For N_2

X-ray Transition	Initial State (n, ℓ)	Final State (n', ℓ')	Energy (keV) [*]
K_{α}	(2,1)	(1,0)	102.406
K_{β}	(3,1)	(1,0)	121.437
K_{γ}	(4,1)	(1,0)	128.091
K_{δ}	(5,1)	(1,0)	131.167

* Reference: R. Engfer et al., 1974

5.2 - N_2 at 4 atm

The individual K series transitions are plotted in Figures 5.2-1 to 5.2-4, for N_2 runs at 4 atm. Each plot contains the actual data as well as the computer fit. Table 5.2-1 tabulates the calculated intensities of each transition and includes the value of χ^2/F for the fit.

Table 5.2-1 Nitrogen K Series Intensities
for 4 atm run.

<u>Transition</u>	<u>Intensity (counts)</u>	<u>χ^2/F</u>
K_α	134196 ± 566	0.97
K_β	10098 ± 200	1.17
K_γ	3664 ± 162	1.27
K_δ	1620 ± 147	1.53

Figure 5.2-1 K_{α} Transition of N₂ at 4 atm

Figure 5.2-2 K_{β} Transition of N_2 at 4 atm

Figure 5.2-3 K_γ Transition of N₂ at 4 atm

Figure 5.2-4 K_δ Transition of N₂ at 4 atm

5.3 - N_2 at 1 atm

The experimental data and computer fitting of the data for the N_2 run at a pressure of 1 atm are shown in Figures 5.3-1 and 5.3-3. Calculated intensities and values of χ^2/F for each fit are listed in Table 5.3-1.

Table 5.3-1 Nitrogen K Series Intensities
for 1 atm run.

<u>Transition</u>	<u>Intensity (counts)</u>	<u>χ^2/F</u>
K_α	6937 ± 143	0.68
K_β	569 ± 73	0.89
K_δ	177 ± 68	0.58

Figure 5.3-1 K_{α} Transition of N_2 at 1 atm

N₂ K BETA 1 ATM.
LINEAR PLOT
SPECTRUM NO. 13

Figure 5.3-2 K_{β} Transition of N_2 at 1 atm

N₂ K GAMMA 1 ATM
LINEAR PLOT
SPECTRUM NO. 13

Figure 5.3-3 K_γ Transition of N₂ at 1 atm

5.4 - N₂ at 0.5 atm

Figures 5.4-1 to 5.4-3 display the K_{α} , K_{β} and K_{γ} transitions of N₂ at a pressure of 0.5 atm. The results of the computer analysis are listed in Table 5.4-1.

Table 5.4-1 Nitrogen K Series Intensities
for 0.5 atm run.

<u>Transition</u>	<u>Intensity (counts)</u>	<u>χ^2/F</u>
K_{α}	18330 $\pm$ 243	1.23
K_{β}	1753 $\pm$ 138	1.25
K_{γ}	865 $\pm$ 133	1.07

Figure 5.4-1 K_{α} Transition of N₂ at 0.5 atm

Figure 5.4-2 K_{β} Transition of N₂ at 0.5 atm

Figure 5_4-3 K_Y Transition of N₂ at 0.5 atm

5.5 - Background Subtraction for K Series Peaks

Muonic atom x-ray transitions are not only produced by cascading muons in the gaseous target atoms, but also in other atoms located in the target area. For example, most of the muons stopped in the aluminium box containing the nitrogen gas as well as in the plastic scintillators used for the muon telescope. The formation of muonic atoms of aluminium, carbon and oxygen caused intense K, L, and M series peaks of these elements. Therefore, the spectra studied for nitrogen lines contained many interfering peaks. One of the contaminating factors was the presence of air in the target area which created background nitrogen peaks not produced by atoms at the desired pressure. To measure the intensities of these background peaks, a run of B_2H_{10} was used. The B_2H_{10} run chosen for the background measurement was a twenty hour run, which provided intense background peaks. Nitrogen K series peaks were present in the B_2H_{10} run and Figures 5.5-1 to 5.5-4 display the data and computer fits for these background peaks. The intensities measured were then normalized to an intense aluminium line $Al_{M\alpha}$ (see Figure 5.5-5). Because the amount of aluminium irradiated by the muon beam was unchanged, this transition was chosen as the normalizing line. Table 5.5-1 lists the intensities of background N_2 K series lines, the $Al_{M\alpha}$ line and the ratio of the nitrogen lines to the aluminium line. Multiplication of the background factors from Table 5.5-1 by the intensity of

Figure 5.5-1 Background N_2 K_α Transition

RUN66 N2 K BETA
LINEAR PLOT
SPECTRUM NO. 13

Figure 5.5-2 Background $N_2 K_\beta$ Transition

Figure 5.5-3 Background N_2 K_γ Transition

RUN66 N2 K DELTA
LOG PLOT
SPECTRUM NO. 13

Figure 5.5-4 Background N_2 K_δ Transition

Figure 5.5-5 Background Al_{Mα} Transition

Table 5.5-1 Background Subtraction Factors For
Nitrogen K Series Transitions.

Transition Line	Intensity (counts)	$I/I(A1_{M\alpha})$
$A1_{M\alpha}$	39973 ± 280	1
$N_{K\alpha}$	4703 ± 138	$.1177 \pm .0036$
$N_{K\beta}$	844 ± 92	$.0211 \pm .0023$
$N_{K\gamma}$	453 ± 88	$.0113 \pm .0022$
$N_{K\delta}$	224 ± 89	$.0056 \pm .0022$

Table 5.5-2 N₂ K Series Background Intensities (counts)

<u>Pressure</u>	<u>Transition:</u>	K_{α}	K_{β}	K_{γ}	K_{δ}
4 atm		8687 ± 271	1557 ± 170	834 ± 162	413 ± 162
1 atm		1662 ± 51	289 ± 32	160 ± 31	---
0.5 atm		8020 ± 250	1438 ± 157	770 ± 150	---

the $Al_{M\alpha}$ line for each pressure run provides the background intensities for that run. Figures 5.5-6 to 5.5-8 show the $Al_{M\alpha}$ lines for the 0.5 atm, 1 atm and 4 atm nitrogen runs. Table 5.5-2 lists the K series background intensities calculated from these measurements.

5.6 - N_2 K Series Intensities

The final intensities for the nitrogen K series were calculated by subtraction of the background counts (Table 5.5-2) from the intensities listed in Tables 5.2-1, 5.3-1 and 5.4-1. The intensities listed in Table 5.6-1, therefore, are x-ray counts caused by radiative transitions during muon cascade in target atoms only.

9L M ALPHA 4 ATM
LOG PLOT
SPECTRUM NO. 13

Figure 5.5-6 Al_{Mα} Transition for 4 atm Run

AL M' ALPHA 1 ATM
LOG PLOT
SPECTRUM NO. 13

Figure 5.5-7 $Al_{M\alpha}$ Transition for 1 atm Run

AL M ALPHA 0.5 ATM
LOG PLOT
SPECTRUM NO. 13

Figure 5.5-8 $Al_{M\alpha}$ Transition for 0.5 atm Run

Table 5.6-1 N₂ K Series Intensities (Counts)

<u>Pressure</u>	<u>Transition:</u>	K_{α}	K_{β}	K_{γ}	K_{δ}
4 atm		125509 $\pm$ 628	8540 $\pm$ 263	2830 $\pm$ 229	1207 $\pm$ 219
1 atm		5276 $\pm$ 152	280 $\pm$ 80	17 $\pm$ 75	---
0.5 atm		10310 $\pm$ 348	315 $\pm$ 209	95 $\pm$ 201	---

CHAPTER VI

MUONIC ATOM X-RAY ANALYSIS II

6.1 - General

Several L series transitions of nitrogen were present in the energy spectra collected by detector Ge4. Unfortunately, intense background peaks of carbon and oxygen interfered with intensity measurements for the L_{α} and L_{β} transitions of nitrogen, and made them unresolvable. The nitrogen L_{α} transition has an energy of approximately 19.03 keV. The interfering peak is the carbon L_{β} transition which has an energy of 18.90 keV. The nitrogen L_{β} transition, with an energy of 25.68 keV was unresolvable from the very intense oxygen L_{α} peak (24.91 keV). However, several N_2 L series transitions were void of interfering peaks. The L_{γ} , L_{δ} and L_{ϵ} transitions of nitrogen were observed (see Figures 6.1-1 to 6.1-3) and measurements of their intensities made. Table 6.1-1 lists the L series transitions for nitrogen and their energies.

6.2 - N_2 at 4 atm

Intensities of the nitrogen L_{γ} , L_{δ} and L_{ϵ} transitions, collected during the N_2 4 atm run, were calculated by the computer fitting program. The data and computer fit for each peak are shown in Figures 6.2-1 to 6.2-2. Table 6.2-1 lists the measured intensities.

Figure 6.1-1 L Series Transitions for N₂ at 4 atm

N2 1 ATM L SERIES •

LINEAR PLOT

SPECTRUM NO. 13

100 COUNTS PER TICK

Figure 6.1-2 L Series Transitions for N_2 at 1 atm

N₂ 0.5 ATM L SERIES

LINEAR PLOT

SPECTRUM NO. 13

Figure 6.1-3 L Series Transitions for N₂ at 0.5 atm

Table 6.1-1 L Series Energies for N_2

<u>x-ray Transition</u>	<u>Initial State (n,l)</u>	<u>Final State (n',l')</u>	<u>Energy (keV)*</u>
L_α	(3,l)	(2,l')	19.03
L_β	(4,l)	(2,l')	25.68
L_γ	(5,l)	(2,l')	28.76
L_δ	(6,l)	(2,l')	30.42
L_ϵ	(7,l)	(2,l')	31.42

where $\Delta l = (l - l') = \pm 1$

* Reference: Computer program by R. J. McKee (N.R.C.)

Figure 6.2. L_γ Transition for N₂ at 4 atm

N₂ L DEL. GAMMA 4 ATM
 LOG PLOT
 SPECTRUM NO. 13

Figure 6.2-2 L_g, L_e, and Transitions for N₂
 at 4 atm

Table 6.2-1 Nitrogen L Series Intensities
for 4 atm run.

Transition	Intensity (counts)	χ^2/F
L_Y	7358 ± 197	1.23
L_δ	4014 ± 174	1.20
L_E	2040 ± 158	1.20

6.3 - N_2 at 1 atm

The nitrogen run at a pressure of 1 atm had a short running time, so that only the $N_2 L_Y$ and L_δ peaks were observed. The computer fits for these transitions are shown in Figures 6.3-1 and 6.3-2. Because the peaks are small, their computer fits contain large errors. Table 6.3-1 lists the intensities calculated by the program.

Table 6.3-1 Nitrogen L Series Intensities
for 1 atm run.

Transition	Intensity (counts)	χ^2/F
L_Y	382 ± 73	1.11
L_δ	148 ± 72	0.97

N₂ L GAMMA 1 ATM
LINEAR PLOT
SPECTRUM NO. 13

Figure 6.3-1 L_γ Transition* for N₂ at 1 atm

Figure 6.3-2 L_{δ} Transition, for N₂ at 1 atm

6.4 - N₂ at 0.5 atm

Figures 6.4-1 to 6.4-2 display the data and computer fits for the L_γ, L_δ and L_ε transitions of the nitrogen 0.5 atm run. The intensities calculated from the fitting program are tabulated in Table 6.4-1.

Table 6.4-1 Nitrogen L Series Intensities
for 0.5 atm run.

<u>Transition</u>	<u>Intensity (counts)</u>	<u>χ²/F</u>
L _γ	2741 ± 156	1.55
L _δ	1628 ± 154	1.33
L _ε	590 ± 145	1.33

6.5 - Background Subtraction for L Series Peaks

The background subtraction technique used for the N₂ L series peaks was similar to that used for the N₂ K series analysis (see Section 5.5). The intensities of background N₂ L series peaks present in the B₂H₁₀ run were calculated. Figures 6.5-1 and 6.5-2 display the background N₂ L_γ, L_δ and

N₂ L GAMMA 0.5 ATM
LINEAR PLOT
SPECTRUM NO. 13

Figure 6.4-1 L_γ Transition for N₂ at 0.5 atm

Figure 6.4-2 L_{δ} and L_{ϵ} Transitions for N_2 at 0.5 atm

Table 6.5-1 Background Subtraction Factors
For Nitrogen L Series Transitions.

Transition Line	Intensity (counts)	$I/I(AI_{M\alpha})$
$AI_{M\alpha}$	39973 ± 280	1
N_{LY}	1119 ± 102	$.0280 \pm .0026$
$N_{L\delta}$	622 ± 103	$.0156 \pm .0026$
$N_{L\epsilon}$	302 ± 97	$.0076 \pm .0024$

Table 6.5-2 N₂ L Series Background Intensities (Counts)

<u>Pressure</u>	<u>Transition:</u>	<u>L_γ</u>	<u>L_δ</u>	<u>L_ε</u>
4 atm		2067 ± 192	1151 ± 192	561 ± 177
1 atm		200 ± 19	111 ± 19	---
0.5 atm		1908 ± 178	1063 ± 177	518 ± 164

RUN66 N2 L GAMMA
LINEAR PLOT
SPECTRUM NO. 13

Figure 6.5-1: Background N₂ L_γ Transition

RUN66 N2 L DEL.EPSILON
LINEAR PLOT
SPECTRUM NO. 13

Figure 6.5-2 Background N₂ L_δ and L_ε Transition

L_{ϵ} peaks. The calculated intensities of these lines as well as their normalization to the $Al_{M\alpha}$ line are listed in Table 6.5-1. Multiplication of these background factors (Table 6.5-1) by the $Al_{M\alpha}$ intensities (see Section 5.5) of each pressure run gives the background intensities for each transition. Table 6.5-2 lists these background intensities.

6.6 - N_2 L Series Intensities

The final N_2 L series intensities are tabulated in Table 6.6-1 and were calculated by subtraction of the background intensities (Table 6.5-2) from the L series intensities listed in Tables 6.2-1, 6.3-1 and 6.4-1. These remaining counts are caused by muon cascade in target atoms only.

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OF/DE

Table 6.6-1 N_2 L Series Intensities (Counts)

<u>Pressure</u>	<u>Transition:</u>	L_γ	L_δ	L_ϵ
4 atm		5291 ± 275	2862 ± 259	1479 ± 238
1 atm		182 ± 75	36 ± 75	---
0.5 atm		833 ± 236	565 ± 235	72 ± 219

CHAPTER VII

RESULTS AND CONCLUSION

The intensities of K and L series transitions, produced by the cascade of muons in nitrogen atoms, were measured for target pressures of 4 atm, 1 atm and 0.5 atm (see Tables 5.6-1 and 6.6-1). The K series intensities were normalized to the $N_2 K_\alpha$ line while the intensities of the L series transitions were normalized to the $N_2 L_Y$ peak. Tables 7.1-1 and 7.1-2 lists these normalized intensities for each pressure of the nitrogen gas target.

Comparison of the intensities obtained for different pressures of the target atoms provides information about the refilling time of the electronic shells. Since the refilling time is dependent upon the collision rate of target atoms and hence the pressure, it is expected that the intensity ratios IK_B/IK_α , IK_Y/IK_α etc. would differ from one pressure run to the next. This of course is the observed result as seen in Tables 7.1-1 and 7.1-2.

The errors calculated for the intensity ratios are large in some cases because of the size of the peaks. The K_Y and K_δ transitions, for example, produced small peaks which contained a large background contribution. As described previously, contaminating nitrogen atoms which were not at target pressures caused these background counts. These

Table 7.1-1 Muonic Atom X-Ray Intensities*
for the K Series Transitions
of Nitrogen

Pressure of N ₂ Gas	Transition: $\frac{1}{2}$	K _{α}	K _{β}	K _{γ}	K _{δ}
4 atm	1	.0680 $\pm$.0021	.0225 $\pm$.0018	.0096 $\pm$.0017	---
1 atm	1	.053 $\pm$.015	.003 $\pm$.014	---	---
0.5 atm	1	.031 $\pm$.020	.009 $\pm$.019	---	---

* Intensities normalized to the N₂ K _{α} intensity.

Table 7:1-2 Muonic Atom X-Ray Intensities*
for the L Series Transitions
of Nitrogen.

Pressure of N ₂ Gas	Transition: L _γ	L _δ	L _ε
4 atm	1	.541 ± .057	.280 ± .047
1 atm	1	.20 ± .42	---
0.5 atm	1	.68 ± .34	.09 ± .26

* Intensities normalized to the N₂ L_γ intensity.

counts were subtracted from each run leaving intensities only attributable to N_2 atoms at the desired pressure. This produced large errors in the final results since the stop rate of muons in the target gas was extremely small, especially at pressures of 1 atm and 0.5 atm (see Table 5.6-1 and 6.6-1).

The cascade program (see Section 2.3) was used to calculate the refilling times necessary to produce intensity ratios observed during the experiment. The program was run for refilling times ranging from 1.0×10^{-14} sec to 1.0×10^{-9} sec and an initial weighted statistical distribution of $(2\ell + 1)e^{a\ell}$ where $a = .2$ (see Section 2.3). Intensity ratios were calculated from the cascade program for K and L series radiative transitions, and are listed in Table 7.1-3. A comparison between the intensity ratios calculated theoretically by the cascade program, and the intensity ratios measured from the experimental data allowed a determination of the refilling times for each pressure of the nitrogen target. Figure 7.1-1 displays graphically, the theoretical calculations for the intensity ratio ($I_{K\beta}/I_{K\alpha}$) of nitrogen versus the refilling time of the electronic states. Included on the graph are the experimental ratios for each pressure run. The results are consistent with the statement that reducing the pressure of the target gas prolongs the refilling of the electronic shells. The position of the experimental ratios on the graph (Figure 7.1-1)

Table 7.1-3 N₂ K and L Series Intensities* as Predicted by the Cascade Program for Several Values of the Refilling Time Parameter.

Refilling time (sec)	Transition:					
	K _α	K _β	K _γ	K _δ	L _γ	L _ε
10 ⁻⁹	1	.0132	.0025	.0023	1	.43
10 ⁻¹⁰	1	.0192	.0042	.0022	1	.41
10 ⁻¹¹	1	.0361	.0104	.0052	1	.53
10 ⁻¹²	1	.090	.046	.028	1	.41
10 ⁻¹³	1	.147	.088	.040	1	.282
10 ⁻¹⁴	1	.186	.092	.028	1	.229

* K series intensities normalized to K_α intensity.

L series intensities normalized to L_γ intensity.

Figure 7.1-1 Graph of intensity ratio (I_{K_g}/I_{K_a}) versus refilling time as calculated by cascade program.

Refilling Time

indicate refilling times in the order of 1.0×10^{-12} sec and 1.0×10^{-11} sec for nitrogen pressures ranging from 4 atm to 0.5 atm. Table 7.1-4 lists the results as obtained from the graph in Figure 7.1-4.

Table 7.1-4 Cascade Program Predictions of Refilling Times for each Pressure of Nitrogen Gas used during the Experiment.

Pressure of N ₂ Gas	Refilling time of K and L Electronic Shells
4 atm	$(2.5 \pm 0.3) \times 10^{-12}$ sec
1 atm	$(4.5 \pm 4.6) \times 10^{-12}$ sec $- 2.0$
0.5 atm	$(1.5 \pm \infty) \times 10^{-11}$ sec $- 1.0$

These refilling times assume that the uncertainties in the cascade calculations are small. Previous experiments in muonic atom x-ray intensities have verified the calculations performed by the cascade program.

Now that a determination of the refilling times for the nitrogen targets has been made, the observability of

the two photon decay of the $2S_{1/2}$ state can be considered. If the two photon transition is to be the dominant decay mode of the $2S_{1/2}$ state, the competing Auger transitions must be suppressed. Therefore, the refilling times of the electronic shells should be longer than the time it takes the muon to cascade to the $2S_{1/2}$ state and then decay to ground state by radiative transitions. If the cascade time to the $2S_{1/2}$ level plus the lifetime of the $2S_{1/2}$ state is shorter than the refilling times, then the probability of observing the two photon $2S_{1/2} \rightarrow 1S_{1/2}$ transition would be greatly enhanced. Theoretical predictions of these times are included in the cascade calculations and are listed in Table 7.1-5 for various values of the refilling time parameter. Observation of the two photon decay for the $2S_{1/2}$ state will be more probable for refilling times in the order of 1.0×10^{-9} sec, since the time taken for the muon to cascade to that state and then decay to ground state will be shorter than the time taken for refilling of the electronic shells. Therefore, of the three pressures used during the experiment, nitrogen gas at 0.5 atm offers the most suitable refilling times necessary for observation of the two photon decay from the $2S_{1/2}$ state of muonic nitrogen. Unfortunately, many muons must be stopped in the low pressure gas target to observe this decay since only 1% of all muons cascading to ground state will reach the $2S_{1/2}$ level. In order to populate this state with appreciable numbers of muons so that observation of the two photon decay is

Table 7.1-5 Muon Cascade Times to the $2S_{1/2}$ State and
 $2S_{1/2}$ State Lifetimes as Predicted by
 Cascade Program if $Z = 7$ and the Initial
 Distribution is $\rho(l) = (2l + 1)e^{0.2l}$ ($n_0 = 14$)

Refilling Time (sec)	$2S_{1/2}$ Cascade Time (sec)	$2S_{1/2}$ Lifetime (sec)
1.0×10^{-14}	11.78×10^{-14}	0.66×10^{-9}
1.0×10^{-13}	2.63×10^{-13}	0.66×10^{-9}
1.0×10^{-12}	1.29×10^{-12}	0.66×10^{-9}
1.0×10^{-11}	0.77×10^{-11}	0.66×10^{-9}
1.0×10^{-10}	0.32×10^{-10}	0.66×10^{-9}
1.0×10^{-9}	0.08×10^{-9}	0.85×10^{-9}

possible experimentally, a large capture rate of muons in the target gas is required. In conclusion, observation of the two photon decay from the $2S_{1/2}$ state will be extremely difficult since refilling times in the order of 1.0×10^{-9} were not obtained by the gas pressures used. Nitrogen runs at a pressure of 0.5 atm seem to provide best opportunity of observing the two photon decay since it has the longest refilling time. The small stopping rate of muons in the target gas at this pressure however, will reduce the probability. Observing the two photon decay from the 4 atm and 1 atm nitrogen runs will be unlikely since the Auger effect will still have a competing decay contribution.

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