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**Autoionization of Be-like Ions Following
Double Electron Capture In C^{4+} , O^{6+}
and Ne^{8+} Ions**

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Abstract

This paper describes electron emission following the autoionization of doubly excited states in Be-like ions. The Be-like Auger states are produced by two electron capture in slow C^{4+} , O^{6+} and Ne^{8+} ions. These measurements were performed by means of high resolution Auger electron spectroscopy on different target gases and at different projectile energies. Line assignments and relative cross sections are given for the investigated doubly excited states and the excitation mechanism is discussed.

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1 Introduction

The availability of intense highly charged heavy ion beams at low velocities from sophisticated ion sources (e.g., ECR-Electron Cyclotron Resonance-source, EBIS-Electron Beam Ion Source) enables the performance of detailed studies of multi-electron capture processes. These investigations are important to both basic and applied physics. The wealth of spectroscopic and cross section data which can be deduced are helping to shape an understanding of the physics in high temperature dense plasmas as they are used in fusion research and x-ray laser research. The multi-electron transfer processes can be investigated generally by measuring the x-ray or electron emission following radiative or non-radiative deexcitation, or by analyzing projectile charge states, recoil ion charge state distributions and coincidence measurements. The study of highly excited states also allows an investigation of exotic atomic structures as they are present in a plasma. For example, the ability to selectively excite states in a collision via capture using preselected ion charge states in a groundstate configuration could furthermore be of interest in pumping schemes where additional laser excitation will be employed. By varying the projectile energy or angle of observation in ion collision experiments further investigations of the excitation processes are possible.

Many of the relevant ion collision studies at slow collision velocities have been performed by the techniques of high resolution Auger electron spectroscopy. Most of these studies have been performed using ions that ranged in atomic numbers up to $Z=29$. For those ions, ion beams with sufficient

intensities at high charge states are easily produced in a continuous beam mode in ECR sources. The Auger electron yields for the doubly excited states are still sufficient to allow high resolution Auger spectroscopy. This presentation reports results from high resolution Auger electron spectroscopy studies where the projectile energy has been varied to some extent, and where different target gases have been used. A comparison is made between calculated transition energies of the data collected here and recently published results. Results from related coincidence measurements where projectile centered continuum electrons have been measured in coincidence with the charge changed projectile ions are also presented.

1.1 Multiple Electron Capture in Slow Highly Charged Ion - Atom Collisions

The process discussed here is the single collision interaction between He-like projectile ions (C^{4+} , O^{6+} , Ne^{8+}) and neutral inert gas target atoms (He, Ne, Ar), in which one, two or three electrons are transferred to the projectile to form excited states (Auger) in the projectile. The process in which two electrons are transferred is termed Double electron Capture (DC), if more electrons are transferred the process is termed Multiple electron Capture (MC). These processes are studied by observing the decay (autoionization) of the excited projectile states. The general form of this reaction can be written

$$A^{q+} + B \rightarrow A^{(q-s)+} ** + B^{s+} \rightarrow A^{(q-s+1)+} + B^{s+} + e_A^-, \quad (1)$$

where s is the number of transferred electrons. We observe the emission of the e^- following the Auger decay of the doubly excited projectile.

1.2 Theory of Auger Transitions

The Auger effect was discovered by P. Auger in 1925 [1] and a correct nonrelativistic theory was presented by G. Wentzel in 1927 [2]. According to Werner Mehlhorn[3] "Auger and autoionizing states are excited quasi-discrete states of a system which are embedded in the continuum of the next higher charge state of the system". These excited states can decay either by the emission of an electron without radiation or by the emission of radiation. The former is the dominant decay mode unless the transition energy is very large ($E_T > 5$ keV). The radiationless decay mode (electron emission) is called an autoionizing or Auger transition, depending on whether the excited quasi-discrete state occurs in a neutral atom or in an atom ionized in an inner-shell. For example, in a Ne ion an autoionizing state can be formed either by excitation of an inner-shell electron (1s or 2s) to an empty but bound orbital or by excitation of two electrons of the outermost 2p shell to discrete states. These states are shown in Figure 2. An Auger state is created by inner-shell ionization. A typical Ne -K Auger spectrum is shown in Figure 1 where the Auger states were excited by 4.2MeV H^+ , 3.2keV e^- and 1.5keV X-rays.

With the Ne atom K-shell ionization creates the Auger state causing the emission of a K Auger electron. The 2s-ionization leads to an excited Ne^+ ion with an energy still below the continuum threshold of Ne^{++} , therefore,

Figure 1: Ne K-Auger spectrum.

From N. Stolterfoht [4].

Figure 2: Ne energy level diagram.

from Mehlhorn[3]

it decays only by the emission of radiation. When the initial state is such that there is more than one vacancy the corresponding Auger transitions are called satellite transitions. In the energy level diagram of Figure 2 only the initial and final atomic and ionic states are included, the Auger transitions are indicated by the arrows connecting the relevant atomic states. The energy of the ejected electron is given by the difference between the initial and final states.

In non-relativistic theory both Auger and autoionizing transitions are

caused by the Coulomb interaction $\frac{e^2}{r_{12}}$ between the electrons that participate directly in the transition. As an example, consider an Auger transition with initial and final states for the total system (atom + electron) in LS -coupling of the neon atom, according to Davydov [5]:

$$\Psi_i = \Psi(1s2s^22p^6; S_i L_i M_{S_i} M_{L_i}) \quad (2)$$

$$\Psi_f = \Psi(1s^22s^22p^4(SL)E\ell; S_f L_f M_{S_f} M_{L_f}), \quad (3)$$

where E and ℓ are the energy and orbital angular momentum of the Auger electron. The transition probability from state $\Psi_i \rightarrow \Psi_f$ is given by Wentzel [2] as:

$$P_{i \rightarrow f} = \frac{2\pi}{\hbar} |\langle \Psi_f(S_f L_f M_{S_f} M_{L_f}) | \sum_{i>j} \frac{e^2}{r_{ij}} | \Psi_i(S_i L_i M_{S_i} M_{L_i}) \rangle |^2 \delta(E_i - E_f - E) \rho(E), \quad (4)$$

where $\rho(E)$ is the density of the continuum states of the Auger electron and $\delta(E_i - E_f - E)$ is a representation of energy conservation. The matrix element in equation (4) is non-zero only if the selection rules for the Coulomb interaction $\frac{e^2}{r_{ij}}$ are fulfilled. Since this is pure LS -coupling,

$$S_i = S_f, L_i = L_f, M_{S_i} = M_{S_f}, M_{L_i} = M_{L_f} \quad (5)$$

and as always $J_i = J_f, M_i = M_f, \pi_i = \pi_f$. The parity π of the total system is given by

$$\pi = (-1)^{\sum \ell_i}. \quad (6)$$

Note that in equation (4) Ψ_i and Ψ_f differ in only two spin orbitals, $2p^2$ in Ψ_i and $1s E\ell$ in Ψ_f . The Coulomb interaction $\frac{e^2}{r_{12}}$ is a two-particle operator

Figure 3: Decay of Auger state.

from Mehlhorn[3]

Figure 4: Double differential cross section of ejected Auger electrons

from Mehlhorn[3]

and causes the transition $2p^2 \rightarrow 1s E\ell$, the other electrons do not contribute to the interaction except as spectator electrons which are the source of the effective atomic potential. An Auger transition has two possible paths **a** and **b** as shown in Figure 3. The paths **a** and **b** are given by

$$a) P + A \rightarrow P + A^+ + e^-(E_1) \rightarrow P + A^{++} + e^-(E_1) + e^-(E_{Auger}) \quad (7)$$

$$b) P + A \rightarrow P + A^+ + e^-(E_1). \quad (8)$$

Path **b** is negligible because of the small probability amplitude due to the double ionization process and the fact that both electron energies, E_1 and E_{Auger} , should be the same as in path **a**. Since $d^L \cong 0$ and $d^L \cong 0$, then

$$\left(\frac{d^2 \sigma}{dE d\theta} \right)_{direct} = 0 \quad (9)$$

$$a = 0 \quad (10)$$

$$b = \frac{I(\theta)}{\frac{\Gamma}{2}} \quad (11)$$

and equation (4) becomes

$$\left(\frac{d^2 \sigma}{dE d\theta} \right) = \frac{2\pi}{\Gamma} \frac{I(\phi)}{1 + \epsilon^2} = I(\phi) \frac{\frac{\Gamma}{2\pi}}{(E - E_r)^2 + \frac{\Gamma^2}{4}} \quad (12)$$

where $I(\phi)$ is the intensity of the Auger line observed in the direction ϕ . Equation (12) gives the symmetrical Lorentz-line of Figure 4.

1.3 Kinematic Effects

If the autoionization electrons are emitted from a moving emitter they exhibit kinematic effects. The autoionization lines are modified in position,

width and intensity. The projectile energy is varied in order to study the kinematic aspects of the excitation process.

a) Position

The relative velocities of the emitting ion and the emitted electron are depicted in Figure 5 where V_P is the velocity of the emitting ion in the laboratory reference frame, V_A and V'_A are the velocity of the autoionized electron in the laboratory and center of mass reference frame respectively, and finally θ and θ' are the emission angles in the laboratory and center of mass reference frame respectively. Relating the velocity to the energy yields

$$\begin{aligned} V_P &= \sqrt{\frac{2 E_P}{m_p}}, \\ V_A &= \sqrt{\frac{2 E_A}{m_e}}, \\ V'_A &= \sqrt{\frac{2 E'_A}{m_e}}. \end{aligned} \quad (13)$$

It can be seen from Figure 5 and above that

$$\begin{aligned} E'_A \sin \theta' &= E_A \sin \theta, \\ E'_A \cos \theta' &= E_A \cos \theta - \sqrt{E_P \frac{m_e}{m_p}}, \end{aligned} \quad (14)$$

which when squared and added yield

$$E'_A = E_A - E_P \frac{m_e}{m_p} - \sqrt{E_A E_P \frac{m_e}{m_p}} \cos \theta. \quad (15)$$

The quantity

$$E_P \frac{m_e}{m_p} \quad (16)$$

Figure 5: Kinematic velocity vectors.

is just the energy of the electrons that travel with the ion beam. These electrons are called *cusp electrons* and are denoted as E_c and equation 15 becomes

$$E'_A = E_A - E_c - \sqrt{E_A E_c} \cos \theta. \quad (17)$$

In these experiments the viewing angle θ is zero degrees. This allows electrons emitted at angles of 0 and 180 degrees to enter the analyzer causing in principal two groups of autoionization peaks one above and one below the cusp energy. The peak energies as shown in Figure 6 are denoted E_H and E_L and are given by:

$$E_{H/L} = \left(\sqrt{E_c} \pm \sqrt{E'} \right)^2, \quad (18)$$

or as

$$\begin{aligned} E_H &= E_c + E' + 2\sqrt{E_c E'}, \\ E_L &= E_c + E' - 2\sqrt{E_c E'}. \end{aligned} \quad (19)$$

Figure 6: Autoionization spectra showing high-low emission pairs.

From T. Schneider [6].

In relativistic terms these are given by:

$$\begin{aligned} E_r^H &= \frac{1}{C^H} \left(\sqrt{E_c} + \sqrt{E'} \right)^2, \\ E_r^L &= \frac{1}{C^L} \left(\sqrt{E_c} - \sqrt{E'} \right)^2, \end{aligned} \quad (20)$$

where

$$\begin{aligned} C^H &= \left(1 + \frac{2\sqrt{E_c E'}}{c^2} \right)^2, \\ C^L &= \left(1 - \frac{2\sqrt{E_c E'}}{c^2} \right)^2. \end{aligned} \quad (21)$$

b) Width

The width of the autoionization lines is different when viewed in the center of mass reference frame than when viewed in the laboratory reference

frame. ΔE changes from the laboratory to the center of mass rest frame as

$$\Delta E' = \sqrt{\frac{E'}{E}} \sqrt{1 - \frac{E_c}{E'} \sin^2 \theta} \Delta E. \quad (22)$$

The width of the autoionized electron peaks is also effected by azimuthal broadening and polar broadening, these will not be discussed here as the viewing angle of 0 degrees was selected to minimize their effects.

c) Intensity

The intensity of the autoionization lines is given as a function of emission angle and energy of the electron such that

$$Z(\theta, E) = \frac{d^2 \sigma(\theta, E)}{d\Omega dE} \times \Delta E \times \Delta \Omega \times f, \quad (23)$$

where ΔE describes the width, $\Delta \Omega$ describes the solid angle and f describes experimental parameters that are not effected by the kinematic energy of the emitter. From this the formula for the double differential cross section follows as:

$$\frac{d^2 \sigma(\theta, E)}{d\Omega dE} = \frac{Z(\theta, E)}{\Delta E \times \Delta \Omega \times f}. \quad (24)$$

The solid angle is changed from the laboratory to the center of mass reference frame as:

$$d\Omega' = \left(\frac{E}{E'} \right) \left(1 - \frac{E_c}{E'} \sin^2 \theta \right)^{-\frac{1}{2}} d\Omega. \quad (25)$$

Therefore the double differential cross section changes from the laboratory to the center of mass reference frame as

$$\frac{d^2 \sigma}{d\Omega dE} = \sqrt{\frac{E}{E'}} \frac{d^2 \sigma'}{d\Omega' dE'}, \quad (26)$$

the solid angle of the analyzer as

$$d\Omega' = \left(\frac{E}{E'} \right) \Delta\Omega, \quad (27)$$

and the change in width as

$$\Delta E' = \sqrt{\frac{E'}{E}} \Delta E. \quad (28)$$

2 Experimental

2.1 Experimental Setup Overview

Most of the electron spectra presented in this thesis were collected at the Lawrence Berkeley Laboratory Electron Cyclotron Resonance-Source (ECR) which has been setup as an injector for the 88" LBL cyclotron. The atomic physics beam-line and 70 degree switching magnet have been installed by the Lawrence Livermore National Laboratory. The McPherson spherical analyzer and scattering chamber are on loan from the University of Texas at Austin. The ECR ion beam in our experiments is collimated down to a 2×2 mm spot size and focused through a gas cell where it interacts with a target gas. The excited projectile ions decay by autoionization. The autoionization electrons are separated from the ion beam by a parallel plate spectrometer that is used as a deflector, routed through a spherical spectrometer, analyzed and finally detected by a channeltron detector. The voltage on the spectrometers is varied to produce the spectra. The channeltron output is amplified and discriminated against electronic noise, then counted and normalized to the

ion beam current. The computer control, data analysis and storage of this setup is provided by a desk-top computer running the program BEN [7]. This setup is depicted in Figure 7.

2.2 ECR Source, Ion Beam and Gas Target

a) ECR Source

The ECR source consists of a magnetic confinement vessel made up of a magnetic sextapole tube into which the beam source molecules are placed and held while they are excited by 2 stages of radio frequency energy. As the molecules in the confinement vessel are ionized by the radio frequency energy they are accelerated into the beam line by an electrostatic accelerator at its exit. The proper charge to mass ratio is selected at the 90 degree bending magnet and the 70 degree magnet steers the ion beam into the atomic physics beam lines, see Figure 7.

b) Gas Cell

The gas cell is comprised of two coaxial cylinders made of brass electrically insulated from each other and ground to allow independent electrical biasing of the two cylinders. The cylinders have closed ends except for a 4 mm square hole centered in each face. The diameter and length of the outer and inner cylinders are 20, 40 and 15, 38 mm respectfully. The exit of the outer cylinder is 108 mm from the input slits of the deflector. The gas in the cell was regulated to a pressure of about 1×10^{-5} torr. The pressure in the cell was chosen after extensive pressure dependence testing to ensure single

Figure 7: Overview of experimental setup.

a) shows a layout of the major components involved in production and transport of the ions, b) shows a schematic layout of the electron spectrometer.

collision conditions were met for each of the three target gases.

2.3 Parallel Plate Spectrometer

a) Description of the Parallel Plate Spectrometer

The parallel plate spectrometer that was used to separate the electrons emitted after the ion target interaction is depicted in Figure 8 a. The parallel plate analyzer is comprised of top and bottom gold plated brass plates separated by 15 mm with 5 equally spaced stainless steel fringe field reducers connected in series to the top and bottom plates through six $7.5 \text{ M}\Omega$ resistors. The entrance and exit apertures are formed by two slits that are 2 mm wide and 10 mm long and separated by 50 mm. This geometry yields a solid angle of about 10^{-3} sr up to the entrance of the second stage analyzer and an energy resolution of 10% (FWHM).

b) Equations of Motion For Parallel Plate Analyzers

As charged particles enter the electric field in the region between the parallel plates their trajectories are changed by the Lorentz forces acting upon them. The equation for an electron's path in the region between the parallel plates of Figure 8 b is given by

$$z = -\frac{V x^2}{4V_e \cos^2(\theta)} + x \tan \theta \quad (29)$$

and the length of the base is given by

$$x_o = 2 \frac{V_e}{V} \sin(2\theta). \quad (30)$$

First order focusing occurs at the exit slit for electrons with entrance angles close to 45 degrees.

Figure 8: Parallel plate analyzer geometry

c) Resolution of the Parallel Plate Spectrometer

The rate of change of x_o with respect to the electron energy leads to the resolution on the parallel plate analyzer,

$$\frac{dx_o}{dV_e} = \frac{2}{V} \sin(2\theta). \quad (31)$$

This has a maximum value when $\theta = 45$ degrees. Using $\theta = 45^\circ$ in $\frac{dx_o}{dV_e} = \frac{2}{V}$ and equation 30 the energy resolution is given by

$$\frac{dx_o}{x_o} = \frac{dV_e}{V_e} = \frac{2\Delta x}{x_o}. \quad (32)$$

This simple formula is only justified for small variations around 45 degrees, which falls well within the limits set up by the apertures.

d) Spectrometer Constants

The deflecting voltage V_D for electrons accelerated through a potential of V_e is given by

$$V_D = \frac{2aV_o}{x_o}. \quad (33)$$

The maximum height that electrons can achieve in the analyzer with the restriction of $\alpha = \pm 3^\circ$ occurs at 48° and is $0.275x_o$, therefore use $a = 0.3x_o$ to allow clearance for the electrons. Using $a = 0.3x_o$ in equation 33 yields a spectrometer constant of 0.6 or

$$V_D = 0.6V_e. \quad (34)$$

Note that there is no focusing in the y direction and the acceptance of the analyzer depends upon its physical size and the small acceptance angle.

2.4 Spherical Spectrometer

a) Discription of the Spherical Spectrometer

The spherical spectrometer is comprised of two concentric spherical segments of cast and machined aluminum with a mean radius of 36 cm and a gap of 8 cm. The spherical segments form an arc of 157.5 degrees when viewed from the top. The focal length distance from the ends of the spectrometer is 7.3 cm. The spherical analyzer is commercially available from the McPherson Instrument Corporation[8].

b) Equations of Motion For Spherical Spectrometer

The equations of motion for a charged particle in the region of the spherical spectrometer are governed by the radial electric field $\{\mathcal{E}(r)\}$

$$\mathcal{E}(r) = \frac{V_f R_1 R_2}{(R_2 - R_1)r^2}, \quad (35)$$

and the radial part of the equation of motion is given by

$$\ddot{r} - r\dot{\phi}^2 = -\mathcal{E} \frac{e}{m} = \frac{k^2}{k^2}, \quad (36)$$

which with $A = r^2\dot{\phi}$, $k^2 = av_o^2$ and $r = 1/u$ can be written as

$$\frac{d^2u}{d\phi^2} + u = \frac{k^2}{A^2}, \quad (37)$$

the integral of which is

$$u = B \cos \phi + C \sin \phi + \frac{k^2}{A^2}. \quad (38)$$

$R_1 = 320 \text{ mm}$	$\beta = 28 \text{ Degrees}$
$R_c = 360 \text{ mm}$	$\alpha = .47 \text{ Degrees}$
$R_2 = 400 \text{ mm}$	$a = 0.254 \text{ mm}$

Figure 9: Spherical analyzer geometry

c) Calculation Of Focusing Voltage

The electric field $\{\mathcal{E}(r)\}$ required to pass electrons of a given energy through a spherical condenser shown in Figure 9 is given by equation (35) above. The condition for a circular orbit requires that

$$\mathcal{E}(r) = \frac{r_o m v_o^2}{e r^2}. \quad (39)$$

Using the kinetic energy relation for an electron $m v_o^2 = 2 e E$ the focusing voltage V_f can be expressed as:

$$V_f = E \left(\frac{R_2}{R_1} - \frac{R_1}{R_2} \right) \text{ or as } V_f = E C, \quad (40)$$

where V_f is the potential difference between the inner and outer spherical plates, E is given in electron volts (eV) and $C = \left(\frac{R_2}{R_1} - \frac{R_1}{R_2} \right)$ is the spectrometer constant.

	Parallel Plate	Spherical
$\frac{\Delta E}{E}$	0.08	0.02
Slits ^a	2×10	0.25×10.16
Spectrometer Factor	0.6	0.45
Electric Field ^b	$\frac{V}{d}$	$\frac{V_f R_1 R_2}{(R_2 - R_1)r^2}$
Solid Angle ^c	0.185	0.00203

^a mm

^bVolts/cm

^cHorizontal (steradian)

Table 1: Spectrometer summary.

d) Resolution

The energy resolution of these concentric spherical analyzers is given by

$$\Delta E = \frac{E \left(a + \frac{2 \alpha^2 r_o}{4} \right)}{2 r_o}, \quad (41)$$

where α is the angle of entrance of the electrons into the analyzer and a is the baffle opening width, see Figure 9. Several characteristics of parallel plate and spherical spectrometers are tabulated in Table 1 for comparison. The overall resolution of the analyzing system is determined by the exit slit width of the spherical analyzer. It is measured to be 2% (FWHM) which agrees well with the calculated value.

e) Calculation of Trajectory

The calculation of the electron focal lengths and trajectories for the spherical analyzer were carried out with the aid of a computer code General Ion Optical System (GIOS) developed by H. Wollnik [9] at Universität, Giessen. The GIOS calculations are in agreement with the experimental data. The

Figure 10: Coincidence setup.

program GIOS was run on a VAX computer at the Physics Department of the University of Texas at Austin. The GIOS input and output files are presented in Appendix A. The program is not listed because of its extended length (i.e. $\simeq 22000$ lines).

2.5 Coincidence Measurement Setup

The basic zero degree experimental setup was modified in order to investigate coincidence of the arrival of the emitted autoionized electron and the arrival of the ion in the final charge state at an ion detector. The coincidence setup is depicted in Figure 10. The final charge state to be studied is placed on the detector by selecting voltage on the electrostatic deflection plates. The arrival time of the selected charge state is then compared with that of the emitted electron to check for coincidence.

3 Results and Discussion

3.1 Doubly excited states in Be-like ions

The electron emission following the decay of autoionizing transitions from doubly excited states in Be-like carbon, oxygen and neon ions has been measured with high energy resolution. The excited states are formed according to the reaction :

$$A^{q+} + B \rightarrow A^{(q-2)+ **} + B^{2+} \rightarrow A^{(q-s+1)+} + B^{s+} + e_A^-, \quad (42)$$

Peak	n	Theory	40 keV		60 keV	
			Experiment		He	Ne
1	5	3.10	3.09	2.85	3.15	2.91
2	6	4.60	4.48	4.54	4.60	4.48
3	7	5.50	5.51	5.11	5.51	5.45
4	8	6.09	6.18	6.18	6.12	6.18
5	9	6.49	6.66	6.60	6.48	6.65
6	10	6.78			6.84	6.90
7			17.26	17.02	17.44	17.38
8			21.01		21.01	

Transition energies following C^{4+} interactions on He and Ne. Energies given in eV.

Table 2: C^{4+} on He and Ne data comparison.

where the $\star\star$ indicates that the ion is in an excited state. The incident ion energy is about $(10\text{kV} \times q)$ keV. In the following the experimental results are presented for the different cases.

3.2 Carbon Ions

a) Autoionization in C^{4+} on He Collisions

Figure 11 shows carbon spectra measured at two different incident C^{4+} ion energies. The ordinate is the relative cross section in arbitrary units and the mantissa is electron volts in the center of mass system. The spectra show rather intense Coster-Kronig lines in contradiction to earlier reported results in reference [10]. The Coster-Kronig lines emitted during the transition

Figure 11: C^{4+} spectra measured at 40 and 60 keV.

for $n = 5$ through 10 are indicated on the 40 keV C^{4+} on He spectra of Figure 11 and the experimental results are tabulated as peaks 1 through 6 in Table 2. The energy E_n of these Coster-Kronig lines were calculated using

$$E_n = X - 13.6 \left(\frac{Z_o}{n^*} \right)^2, \quad (44)$$

where $X = 8.0$ eV is the energy of transition from 2s to 2p from C. E. Moore [11], n^* is the effective quantum number and Z_o is 3 for the final charge state of the C^{4+} . The calculated results are also tabulated in Table 2. The state $1s^2 3d^2$ appears at both energies and with both target species the experimental values for this line position are tabulated as peak number 7 in Table 2. The state $1s^2 3s 3d$ appears at both energies, but only in the interaction with He. The experimental values are tabulated as peak number 8 in Table 2. The experimental results agree well with the theoretical predictions. The intensity ratio between the integrated Coster-Kronig lines and line intensities due to Auger electron emission is found to be 32%. The energy dependence of the Coster-Kronig lines has been measured to some extent by varying the incident ion energy between 40 keV and 60 keV. The state energies are tabulated in Table 2. There seems to be little dependence on the projectile energy when comparing He and Ne at the two energies presented in Figure 11.

b) Autoionization in $\text{C}^{4+} + \text{Ne}$ Collisions

The line widths are nearly equal when comparing the peaks in the He and Ne spectra of Figure 11. This could indicate that the two step double

capture process contributes only a small fraction of the total capture cross section.

3.3 Oxygen Ions

a) Autoionization in O^{6+} on He, Ne and Ar Collisions

Figure 12 shows the center of mass energies of electrons ejected during the interaction between 60 and 80 keV O^{6+} and He, Ne and Ar gas targets. The ordinate is the relative cross section in arbitrary units and the mantissa is electron volts in the center of mass system. The reaction equation for these transitions is given by:

where B represents He, Ne or Ar. The line assignment is tabulated in Table 3 and the data from the He target for peaks 1, 3, 7 and 9 are in agreement with Boudjema[12]. Peaks 12, 13 and 14 have very small cross sections, but still coincide with spectral peaks. It is found that the ratio of line intensities attributed to Coster-Kronig transitions compared to the integrated intensities of lines due to L-Auger electron emission is 26% for 60 keV ion impact and 33% for 90 keV ion impact. This ratio is quite in agreement with the results reported earlier [10]. The relative cross section for the Coster-Kronig and L-Auger electron production is increasing by a factor of two when going from 60 to 90 keV ion impact energies. The peak positions are the same for each of the targets.

Figure 12: O^{6+} spectra measured at 60 and 90 keV.

Peak	60 keV Theory ^a	60 keV Experiment			90 keV		
	He	He	Ne	Ar	He	Ne	Ar
1	20.96	20.73	20.93	20.93	21.36	20.87	21.04
2		23.08	23.15	23.29	23.53	23.36	23.48
3	24.62	24.53	24.53	24.60	24.93	24.51	24.69
4		25.29	25.36	25.50	25.84	25.42	25.48
5		26.96	27.02	27.09	27.29	26.92	27.05
6		27.65	27.79	27.85	27.96	27.79	27.83
7	28.54	28.55	28.55	28.69	28.95	28.69	28.82
8		29.93	30.07	30.14			
9	29.74	30.76	30.83	30.90	30.50	30.26	30.44
10		32.08	32.21	32.21	32.05	32.05	32.05
11		32.89	33.04	33.11			
12	34.02		33.67	33.81			
13	36.94	36.64	36.64	36.71	36.74	36.68	36.56
14	39.70	39.00	39.00	39.07	38.98	39.04	39.04
15		41.21	41.07	41.53	41.22	41.22	41.40
16		43.36	43.43	43.43	43.28	43.40	43.28
17		44.60	44.53	44.53	44.13		44.25
18		45.85	45.78	45.85	45.58	45.76	45.70

Transition energies following O^{6+} interactions on He, Ne and Ar. Energies given in eV.

^aM. Boudjema[12] Their data were shifted by 1.3 eV to obtain a better match.

Table 3: O^{6+} on He, Ne and Ar data comparison.

3.4 Neon Ions

a) Autoionization in Ne^{8+} on He, Ne and Ar Collisions

Figure 13 shows the center of mass energies of electrons ejected during the interaction between 80 and 120 keV Ne^{8+} and He, Ne and Ar gas targets. The ordinate is the relative cross section in arbitrary units and the mantissa is electron volts in the center of mass system. The reaction equation for these transitions is given by:

where B represents He, Ne or Ar. The location of the peaks in the 120 and 80 keV Ne^{8+} on He (DC) interaction are presented in Table 4, they are found to be in agreement with the reported results of M. Bodjema [12] and M. Mack [13]. The relative cross sections are found to increase by a factor of three with an increase of the ion energy from 80 to 120 keV. The relation between Coster-Kronig and Auger line intensities is found to be 31% for 80 keV ions and 36% for 120 keV ions.

Figure 14, shows a comparison of autoionization spectra obtained at much higher ion impact energies using Ne^{6+} ions incident on He. The spectra are shown for comparison with the Ne^{8+} data from slow collisions. Data from fast collisions (MeV energies) using Ne^{8+} ions are not shown, they do not show any intensity due to low lying autoionizing L-shell states. The autoionizing states which are formed in fast collisions with Ne^{6+} ions are most likely formed via transfer excitation rather than by capture or single excitation from a metastable $1s2s2p^2 \ ^3\text{P}$ state which appears to be present in the beam

Figure 13: Ne⁸⁺ spectra measured at 80 and 120 keV.

	80 keV	80 keV			120 keV		
	Theory ^a	Experiment					
Peak	He	He	Ne	Ar	He	Ne	Ar
1		24.78	24.57	24.78	24.30	24.29	24.29
2		28.72	28.62		28.44	28.65	29.48
3			32.66		32.80	32.60	
4					34.05	34.05	
5	35.80	37.65	37.02		37.37	37.99	
6			39.41		39.50	39.45	39.45
7	41.80	42.73	42.42		42.35	42.30	42.35
8		44.19	44.08		44.01	44.22	
9		45.33	45.22		45.05	45.19	45.26
10	46.50	47.09	46.68		46.71	49.67	49.00
12					50.45		
13		51.87	51.56		51.49	51.61	
14					52.32	51.97	
15	52.70	53.53	53.43		53.36	52.58	
16	53.60	54.88	54.78		54.81	55.00	54.81
17		57.99	58.20		58.13	58.27	
18		64.33	63.91		63.94	63.96	

Transition energies following Ne^{8+} interactions on He, Ne and Ar. Energies given in eV.

^aM. Boudjema[12]

Table 4: Ne^{8+} on He, Ne and Ar data comparison.

as in reference [13]. For comparison Auger spectra obtained in very different collisions are shown to illustrate the different mechanisms which can be studied by means of Auger electron spectroscopy. The spectrum in Figure 14 a is obtained at much higher impact energies using 100 MeV Ne^{6+} on He collisions. This spectrum is of interest because it shows pure excitation of the $1s^2 2s 2p \ ^3P$ Be-like metastable state that forms the $1s^2 2s n l \ ^3L$ state which decays into the $1s^2 2s \epsilon \ l$ [14]. This spectrum is taken from reference [15], it has been measured at the VICKSI accelerator at the Hahn-Meitner-Institut in Berlin. The spectrum of Figure 14 b shows the transformed spectrum of Figure 14 a. Electrons following the decay of autoionizing Rydberg states in gas excited 100 MeV Ne^{6+} have been measured with high spectroscopic energy resolution. The ground state configuration of part of the incoming ions is ($1s^2 2s^2$), while the other part consists of a metastable fraction ($1s 2s 2p^2 \ ^3P$) which is about 60% of the beam. This metastable fraction causes the production of the $1s^2 2p \ n l$ excited states by a single electron excitation process. Excitation from the $1s^2 2s^2$ state would require a two electron excitation. The excited states $1s^2 2p \ n l$ decay for Ne^{6+} for $n \geq 7$ via coulomb autoionization. The spectra also show structure in some of the lines which could partly be resolved for the case of $n = 7$ in Ne. The structures could be identified by comparison with calculated transition energies (Dirac-Fock-code). The resolved lower intensity line in peak $n = 7$ in Ne is thus identified as resulting from the decay of the $1s^2 2p \ 7s$ excited state. The equivalent structure in oxygen (peak $n = 6$) is due to the decay of the $1s^2 2p \ 6s$ state. It should further be noted that the intensity in the individual lines decreases with n

Figure 14: High energy Ne^{6+} on He.

indicating the $\frac{1}{n^3}$ -dependence for the excitation of the Rydberg states. The spectrum displayed in Figure 14 c had been measured at the Argonne National Laboratory ECR ion source which can be floated at a high voltage potential of up to 300 kV allowing for ion beams with energies up to 300 kV times the ion charge state. The spectrum appears to be relatively simple as compared to the Ne^{8+} slow impact case, no line assignment is available at present.

b) Autoionization in 10 keV $\times$ q Ne^{10+} on He Collisions

Only weak line intensities are observed for the doubly excited Auger states due to two electron capture. No spectra are presented for this case which is the subject of future studies.

3.5 Coincidence Measurements

Recent studies by Stolterfoht et al reference [4] have shown prominent production of doubly excited final states made up of configurations of highly non-equivalent (HNE) electrons in the process:

By "highly non-equivalent" one means that $n' \gg n$, in fact the states produced have $nl = 2p$ and $n' = 6, 7, 8, \dots$, and reveal themselves via the electron spectrum produced by the Coster-Kronig transition:

The Coster-Kronig lines form a Rydberg progression to the series limit ($n' = \infty$) yielding electrons with a maximum energy of 12 eV in the projectile

frame. The observation of these lines has been taken as strong evidence for correlated behavior of the two active electrons in the capture process. An alternate production mechanism requires single capture at sequential avoided crossings during the collision. If one extends n' into the continuum, one has produced what might be termed ultra non-equivalent (UNE) states, $(nl\ell')$. These would manifest themselves as a final state containing an $O^{5+}(ns^2nl)$ ion and a continuum electron associated with the projectile frame (i.e., a "cusp" electron). These UNE states include those with the O^{5+} produced in the ground state ($1s^22s$); this core is, of course, not observable in the Coster-Kronig spectrum.

To investigate this possibility, an experiment was mounted to measure the zero-degree Auger spectrum in coincidence with charge analyzed final O^{q+} states resulting from O^{6+} on He (and other target) collisions. Figure 10 shows the experimental arrangement. In order to have a measurable coincidence rate it is necessary to increase the width of the slits on the electron spectrometer thus sacrificing resolution. Figure 15 shows the "singles" electron spectrum with the low resolution setup and for comparison, a scan over a wider energy range using the normal high resolution slits and showing the Coster-Kronig progression and higher energy L-Augur lines.

Figure 16 a shows the low energy electron spectrum observed in coincidence with O^{5+} final charge states and Figure 16 b shows the total electron spectrum collected at the same time. These should be compared with Figures 16c and 16d which show the same spectra for the O^{6+} final state (no charge change). The number of electrons coincident with O^{6+} is consistent

Figure 15: Singles spectra.

Figure 16: Coincidence spectra

with zero. The number of electrons observed in coincidence with O^{5+} final projectile charge state expressed as a fraction of the total number of electrons is $15 \pm 2\%$, whereas in the O^{6+} final state it is $0 \pm 2\%$. The peak in the O^{5+} coincidence spectrum, Figure 16 a, is centered at zero energy in the projectile frame indicating association of these events with the "cusp" electrons rather than the "soft collision" electrons resulting from ionization into the target continuum. The singles spectra, Figures 16 b and d, contain contributions from both target and projectile electrons, and are peaked slightly lower in energy. There is an indication of a peak in the O^{5+} coincidence spectrum at the location of the lowest energy Coster-Kronig transition ($2p6l-2s6l'$). The coincidence spectrum has been corrected channel-by-channel for the background due to random coincidences. The gas cell was biased to -40V during these measurements. Because of the low energies of the observed electrons inside the gas cell it is reasonable to expect that the spectrometer collection efficiency may vary significantly over the range studied here. However, the data show that there is at least as much intensity in the cusp peak in coincidence with the O^{5+} projectile final charge state as in the integrated Coster-Kronig spectrum.

4 Conclusion

In this work K and L Auger electron emissions were studied following double electron capture into excited states. The target atoms were He, Ne and Ar gases. The projectiles were relatively slow ($10\text{keV} \times q$) C^{4+} , O^{6+} and

Ne^{8+} ions initially and C^{5+} , O^{7+} and Ne^{9+} after the reaction. The reaction can be described in a three step process. First, the projectile ion approaches the target close enough such that the electrons are shared between both nucleons (i.e. a quasi molecule is formed). Second, the kinetic energy of the projectile nucleus carries it and $q + 2$ electrons away (q is the initial number of electrons on the projectile ion) from the target. Third, since the two electrons that were picked up in the reaction are initially in an excited state the projectile autoionizes ejecting the electrons that are analyzed in the zero degree experimental setup.

It can be seen from the spectra presented in Figures 11, 12 and 13 that the position of the double capture peaks does not depend upon the target gas species and that the overall cross section increases as the target mass and physical size increases. The width of the distribution as a function of projectile energy suggests that the two step process may contribute only a small fraction to the formation of the doubly excited states on top of the single step process. The results from a study of 60 keV O^{6+} on He, Ne and Ar gas targets lead to the conclusion that the double capture occurs predominantly on a fashion that one electron goes into a bound state while the other electron goes into a projectile bound high n - or continuum state. Measurements at higher electron energies in the range where intensity due to K-Auger electron emission would be expected did not show any intensity, indicating that most of the initially He-like ions are in the ground state configuration.

This work has been performed under the auspices of the Department of

Energy and the Robert A. Welch foundation.

Appendix

A GIOS

The GIOS input and output files are reproduced on the following pages.

GIOS INPUT FILE

ELECTRON ANALYZER
REFERENCE PARTICLE .0001 .00054858 1 ;
PHASE_SPACE X .001 .0175 ;
PHASE_SPACE Y .001 .175 ;
CALCULATION ORDER 1 1 ;
APERTURE SLIT .002 .1025 ;
DRIFT LENGTH .02434 ;
FRING FIELD 1 ;
ELECTROSTATIC SECTOR .12 157.5 .013 1 0 0 ;
FRING FIELD 1 ;
DRIFT LENGTH 0.02434 ;
APERTURE SLIT 0.02 .02
DRIFT LENGTH 0.06 ;
PLOT PHASE_SPACE (X,Y) P 1000 0.01 0.03 ;
PLOT BEAM 40 0.02 0.04 ;
END ;

GIOS OUTPUT FILE

45

*** GIOS VERSION T4P ** GIESSEN 1988 *** DATE 18-JUN-90 TIME 16:57:02 ***
 ***** INPUT DATA ***** INPUT DATA *****

1. ELECTRON ANALYZER
 2. REFERENCE PARTICLE .0001 .00054858 1 ;
 3. PHASE_SPACE X .001 .0175 ;
 4. PHASE_SPACE Y .001 .175 ;
 5. CALCULATION ORDER 1 1 ;
 6. APERTURE SLIT .002 .1025 ;
 7. DRIFT LENGTH .02434 ;
 8. FRING FIELD 1 ;
 9. ELECTROSTATIC SECTOR .12 157.5 .013 1 0 0 ;
 10. FRING FIELD 1 ;
 11. DRIFT LENGTH 0.02434 ;
 12. APERTURE SLIT 0.02 .02
 13. DRIFT LENGTH 0.06 ;
 14. PLOT PHASE_SPACE (X,Y) P 1000 0.01 0.03 ;
 15. PLOT BEAM 40 0.02 0.04 ;
 16. END ;

STAT. INFORMATIONS: ERRORS= 0 TYPES= 10 WORDS= 76 VARIABLES= 0
 GIOS INPUT IS COMPLETE, COMPUTATIONS STARTS

*** GIOS VERSION T4P ** GIESSEN 1988 *** DATE 18-JUN-90 TIME 16:57:03 ***
 ***** RESULTS ***** RESULTS *****

 **
 ** ELECTRON ANALYZER
 **

MAGN.RIGIDITY = 3.372308700E-05 TESLAMETER ENERGY= 1.000000000E-04 MEV
 ELEC.RIGIDITY = 1.999804345E-04 MEGAVOLT CHARGE= 1.000000000E+00 UNITS
 VELOCITY = 5.93074902E+06 METER/SEC MASS = 5.485800000E-04 AMU

X - DIRECTION X0.... = 1.000000000E-03 TLU ALPHA = 0.000000000E+00
 TAN(A0) = 1.750000000E-02 BETA = 5.714285714E-02 TLU
 LX.... = 0.000000000E+00 LLU EPS = 1.750000000E-05 TLU

Y - DIRECTION Y0.... = 1.000000000E-03 TLU ALPHA = 0.000000000E+00
 TAN(B0) = 1.750000000E-01 BETA = 5.714285714E-03 TLU
 LY.... = 0.000000000E+00 LLU EPS = 1.750000000E-04 TLU

DEVIATIONS: (K-K0)/K0 = 0.000000000E+00 LENGTH-U:TLU= 1.000000000E+00 METER
 (M-M0)/M0 = 0.000000000E+00 LLU= 1.000000000E+00 METER

 APERTURE SLIT RADIAL 2.000000000E-03 TLU AXIAL 1.025000000E-01 TLU

U1 = 0.000000000E+00 LLU V1 = 0.000000000E+00 LLU
 DRIFT LENGTH = 2.434000000E-02 LLU W = 0.000000000E+00 DEG
 U2 = 2.434000000E-02 LLU V2 = 0.000000000E+00 LLU

 ELEC FF#1. ENTR .ANGLE= 0.000000000E+00 DEG REL.CURV. = 0.000000000E+00
 ELEC
 ELEC SECT DEFL.RADIUS= 1.200000000E-01 LLU DEFL.ANGLE= 1.575000000E+02 DEG
 ELEC SECT PATH LENGTH= 3.298672286E-01 LLU VOLTAGE.. = 2.166454707E-02 KV
 ELEC SECT HALF GAP = 1.300000000E-02 TLU
 ELEC SECT N1= 1.000000000E+00 N2= 0.000000000E+00 N3= 0.000000000E+00

ELEC			
ELEC FF#1. EXIT .ANGLE= 0.000000000E+00 DEG REL.CURV. = 0.000000000E+00			
U1 = 7.026201424E-02 LLU		V1 = -2.308655429E-01 LLU	
DRIFT LENGTH = 2.434000000E-02 LLU		W = -1.575000000E+02 DEG	
U2 = 4.777478662E-02 LLU		V2 = -2.401800581E-01 LLU	
APERTURE SLIT		RADIAL 2.000000000E-02 TLU	
		AXIAL 2.000000000E-02 TLU	
U1 = 4.777478662E-02 LLU		V1 = -2.401800581E-01 LLU	
DRIFT LENGTH = 6.000000000E-02 LLU		W = -1.575000000E+02 DEG	
U2 = -7.657984840E-03 LLU		V2 = -2.631410653E-01 LLU	

BEAM PLOT OF (X,Y) FOR 0 MASSES AT Z = 0.43855 LLU

```

1000 PARTICLES STARTED IN A PARALLELOGRAM-LIKE PHASE SPACE (P)
1000 PARTICLES (100.0%) ARRIVED AT Z = 0.43855      LLU
1000 PARTICLES (100.0%) COUNTED WITHIN THIS WINDOW
  CENTER OF WINDOW    HALF WIDTH    DISTRIBUTION
  X ==      0.0000 +-      0.0010      0.00
  A ==      0.0000 +-      0.0175      0.00
  G ==      0.0000 +-      0.0000      0.00
  D ==      0.0000 +-      0.0000      0.00
  Y ==      0.0000 +-      0.0010      0.00
  B ==      0.0000 +-      0.1750      0.00

```

HORIZONTAL X-RANGE +- 0.010000 VERTICAL Y-RANGE +- 0.030000

[illegible]

(.) FROM 1 TO 25 PER CENT OF MAXIMAL BEAM INTENSITY
 (=) FROM 25 TO 50 PER CENT OF MAXIMAL BEAM INTENSITY
 (+) FROM 50 TO 75 PER CENT OF MAXIMAL BEAM INTENSITY
 (*) FROM 75 TO 100 PER CENT OF MAXIMAL BEAM INTENSITY
 (100 PER CENT IS EQUIVALENT TO 13 PARTICLES)

X-SPECTRUM: COUNTS PER 0.28571E-03 UNIT FOR 71 CHANNELS

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
(01)	0	0	0	0	0	0	0	0	0	0
(11)	0	0	0	0	0	0	0	0	0	0
(21)	0	0	0	0	0	0	0	2	11	27
(31)	50	49	92	90	104	107	109	86	88	75
(41)	50	41	18	1	0	0	0	0	0	0
(51)	0	0	0	0	0	0	0	0	0	0
(61)	0	0	0	0	0	0	0	0	0	0
(71)	0									

Y-SPECTRUM: COUNTS PER 0.85714E-03 UNIT FOR 71 CHANNELS

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
(01)	0	0	0	0	0	0	0	0	0	0
(11)	0	0	0	0	0	0	0	0	0	0
(21)	0	1	16	23	37	35	43	41	35	36
(31)	34	38	51	38	32	34	47	52	30	53

PROJECTION OF (X,Y) ONTO THE Y-AXIS

MAXIMUM DENSITY = 53 PARTICLES PER 0.85714E-03 UNIT
 RMS-HALF-ENVELOPE = 0.62076E-02 UNITS WIDE

BEAM ENVELOPES THROUGHOUT THE SYSTEM
 PARALLELOGRAM-LIKE PHASE SPACE ASSUMED

Z (LLU) Y = 4.000000000E-02 TLU X = 2.000000000E-02 TLU

AS	I	Y XX*****AS	I
	I	YB XX	I
	I	YBBB AX	I
	I	YBBB-AX-----I-----	I
ES	I	BBBBB AX	*****ES
ES	I	YBBBBB AX	*****ES
ES	I	YBBBBBBB AX	*****ES
ES	I	BBBBBBBBB AAX	*****ES
ES	I	BBBBBBBBBB AAX	*****ES
ES	I	YBBBBBBBBBB AAXX	*****ES
ES	I	YBBBBBBBBBBB AAXX	*****ES

```

ES      I      BBBBBBBBBBBBBB AAAX      *****ES
ES      I      BBBBBBBBBBBBBB AAAX      *****ES
ES      I      YBBBBBBBBBBBBBB AAAX      *****ES
ES      I      BBBBBBBBBBBBBB AAAX      *****ES
ES      I      YBBBBBBBBBBBBBB AAAX      *****ES
ES      I      BBBBBBBBBBBBBB AAAX      *****ES
ES      I      BBBBBBBBBBBBBB AAAX      *****ES
ES      I      BBBBBBBBBBBBBB AAAX      *****ES
ES      I      BBBBBBBBBBBBBB AAA      *****ES
ES      I      YBBBBBBBBBBBBBB AAA      *****ES
ES      I      BBBBBBBBBBBBBB AAA      *****ES
ES      I      YBBBBBBBBBBBBBB AAA      *****ES
ES      I      BBBBBBBBBBBBBB AAA      *****ES
ES      I      BBBBBBBBBBBBBB AAA      *****ES
ES      I      BBBBBBBBBBBB AAX      *****ES
ES      I      BBBBBBBBBBBB AAX      *****ES
ES      I      BBBBBBBBBBBB AAX      *****ES
ES      I      YBB3BBBBB AXX      *****ES
ES      I      YBBBBBBB AX      *****ES
ES      I      BBBBBB AX      *****ES
ES      I      YBBB AX      *****ES
-----I-----YBBB-AX-----I-----
.365      I      BB XX      I
          I      Y XX      I
AS*****      Y XX      *****AS
          I      BB XX      I
          I      YBBB AX      I
.411      I      YBBBB AXX      I
          I      YBBBBBB AXX      I
          I      YBBBBBBB AXX      I
          I      YBBBBBBB-AX-----I-----
TOTAL LENGTH OF SYSTEM = 4.385472286E-01

```

NON SYMPL. SYSTEM TRANSFER MATRIX AT PATH LENGTH L= 4.385472286E-01 LLU

X AND Y IN TLU, A AND B IN RAD, G AND D IN PARTS FROM M0 AND K0

```

(X,X )=-1.238755135E+00 (A,X )=-3.970179742E+00 (T,X )= 2.196482692E+00
(X,A )=-6.030841829E-02 (A,A )=-1.000544350E+00 (T,A )= 1.106920049E+00
(X,G )= 0.000000000E+00 (A,G )= 0.000000000E+00 (T,G )= 4.999636360E-01
(X,D )= 2.716230175E-01 (A,D )= 4.817440400E-01 (T,D )= 7.955171465E-01

```

```

(Y,Y )=-1.192842205E+00 (B,Y )=-3.189028603E+00
(Y,B )=-6.103176716E-02 (B,B )=-1.001500489E+00

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END OF INPUT , END OF GIOS RUN

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- END -

DATE FILMED

12 / 28 / 90