K-, L-, AND M-SHELL X-RAY PRODUCTION CROSS SECTIONS FOR BERYLLIUM, ALUMINUM, AND ARGON IONS INCIDENT UPON SELECTED ELEMENTS

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Jack Lewis Price, Jr., B.S., M.S.

Denton, Texas

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Incident 0.5 to 2.5 MeV charged particle beams were used to ionize the inner-shells of selected targets and study their subsequent emission of characteristic x-rays. $^{9}_{4}\text{Be}^{+}$ ions were used to examine K-shell x-ray production from thin F, Na, Al, Si, P, Cl, and K targets, L-shell x-ray production from thin Cu, Zn, Ge, Br, Zr, and Ag targets, and M-shell x-ray production from thin Pr, Nd, Eu, Dy, Ho, Hf, W, Au, Pb, and Bi targets. L-shell x-ray production cross sections were also measured for $^{27}_{13}\text{Al}^{+}$ ions incident upon Ni, Cu, Zn, As, Zr, and Pd targets. M-shell x-ray production cross sections were measured for $^{27}_{13}\text{Al}^{+}$ and $^{40}_{18}\text{Ar}^{+}$ ions incident upon Pr, Nd, Gd, Dy, Lu, Hf, Au, Pb, Bi, and U targets.

These measurements were performed using the 2.5 MV Van de Graaff accelerator at North Texas State University. The x-rays were detected with a Si(Li) detector whose efficiency was determined by fitting a theoretical photon absorption curve to experimentally measured values. The x-ray yields were normalized to the simultaneously measured Rutherford backscattered (RBS) yields which resulted in an x-ray production cross section per incident ion. The RBS spectrum was obtained using a standard surface barrier detector calibrated for to account for the "pulse height defect."

The experimental results are compared to the predictions of both the first Born and ECPSSR theories; each of which is composed of two parts, the direct ionization (DI) of the target electron to the continuum and the capture (EC) of the target electron to the projectile. The first Born describes DI by the Plane-Wave-Born-Approximation (PWBA) and EC by the Oppenheimer-Brinkman-Kramers treatment of Nikolaev (OBKN). ECPSSR expands upon the first Born by using perturbed (PSS) and relativistic (R) target electron wave functions in addition to considering the energy loss (E) of the projectile in the target and its deviation from a straight line trajectory (Coulomb deflection (C)).

The measurements presented show that the first Born theories overestimate the measured results rather significantly for all experiments using the ^{9}Be beams to examine the inner shell x-rays, while the ECPSSR predictions fit the measured data much better. For incident ^{27}Al and ^{40}Ar ions, the measured results are not predicted by the theories. The first Born generally overpredicts the data for low target atomic numbers while underpredicting at high atomic numbers. The ECPSSR theory greatly underpredicts the results (factors of 10^{3} to10^{20}). Reasons for this behavior are dicussed as well as suggestions for future experiments.

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CHAPTER I

INTRODUCTION

The inner-shell of an atom can be ionized by one of three major processes: (i) photoionization, (ii) radioactive decay, or (iii) charged particle excitation. Studying inner-shell excitation and ionization yields much insight into the physics of (i) the structure of an atom, (ii) the interaction between photon radiation and matter, and (iii) the interaction between ions and atoms (particle radiation and matter). The studies of ion-atom collisions resulting in inner-shell ionizations can be divided into light-ion (electron) and heavy-ion (proton and heavier) interactions. The study presented here concerns the interaction of ${}^{9}_{4}\mathrm{Be}^{+}$ incident ions with various targets to study the associated K-, L-, or M-shell ionization processes. Additional results are presented for ${}^{27}_{13}\mathrm{Al}^{+}$ and ${}^{40}_{18}\mathrm{Ar}^{+}$ ions incident upon several targets.

Once a vacancy is produced in the inner-shell of an atom by one of the above processes, the excited atom may then decay by a radiative (x-ray) or non-radiative (eg. Auger) process. The measurement of the x-rays emitted or the electrons ejected during the decay provides a technique to estimate the total inner-shell vacancy production. By using previously measured fluorescence yields (probability for radiative decay), one can convert the measured x-ray production cross section into the total ionization (vacancy) cross section.

General Concepts of Charged Particle Excitation

When a heavy charged particle passes through matter, it loses energy primarily by having numerous interactions with the target atoms' electrons. These interactions could result in an inner-shell vacancy. The process by which the target atom is ionized is very dependent upon two ratios: Z_1/Z_2 and v_1/v_e, where Z_1/Z_2 refers to the ratio of the atomic numbers of the incident projectile and target atom, and v_1/v_e is the ratio of the velocity of the projectile to the velocity of the target electron.

A Coulomb interaction between the incident ion and the target electron may result in exciting the electron into a higher quantum state or (more likely at high projectile energies) directly ionizing the electron to the continuum. This Direct Ionization (DI) process dominates at high incident velocities and very small atomic number ratios ($Z_1/Z_2 \ll 1$ or $v_1/v_e \gg 1$). For lower incident velocities ($v_1 \approx v_e$), the Electron Capture (EC) process begins to become dominant. In this process, an inner-shell electron of the target atom is "captured" or transferred to a bound state of the incident projectile. For very slow ($v_1/v_e < 1$

and $v_1/v_e << 1$) and nearly symmetric ($Z_1/Z_2 \simeq 1$) collisions, a third process called electron promotion is important. As the two atoms (projectile and target) come close during a collision, they form a quasi-molecular orbital system for their accompanying electrons. Transitions between the molecular orbitals and the separated atomic orbitals give rise to inner-shell vacancies after the collision is complete. In the work presented here, the region between the DI plus EC and the electron promotion processes is being probed.

Theoretical Approaches to Charged Particle Ionization

Several theories have been proposed over the years to describe the Direct Ionization process. Some of the most successful theories have been the Binary Encounter Approximation (BEA)[1,2,3] the Semi-Classical Approximation (SCA),[4,5] and the Plane-Wave Born Approximation (PWBA).[6,7] These theories give reasonable predictions for low Z_1 projectiles ($Z_1 \leq 4$) on high Z_2 targets with the best agreement for K-shell ionization and somewhat less reliable results for L- and M-shell ionization.

The Plane Wave Born Approximation (PWBA),[6] derived by Bethe in the early years of this century, was used to describe K-shell Direct Ionization (DI) very effectively. This formalism has since been extended by Walske[8] to include the L-shell ionization and by Khandelwal and Merzbacher[9] (revised by Choi[10]) to include M-shell ionization. Further refinement over the years has been necessary to account for some discrepancies with the available data as new experimental techniques result in more precise data.[11-16]

The electron capture (EC) contribution to target vacancy production was first studied by Oppenheimer[17] and evaluated in the first Born Approximation by Brinkman and Kramers[18] (OBK). In 1966, Nikolaev[19] extended the OBK calculations to include the nuclear-nuclear interactions between the projectile and target atoms. The resulting OBKN theory in the first Born approximation has resulted in fairly good agreement with the data (within an order of magnitude). Further refinement became necessary as more precise experimental techniques were developed.

More recently, Basbas proposed a theory that is similar to the PWBA formalism for DI but takes into account the increased binding effect on the target electrons by a slow projectile which penetrates the target electron orbitals and polarization of the orbital by a large impact parameter projectile. This theory, the Perturbed Stationary State (PSS) Theory,[11,12,13,20,21] has been modified by Brandt and coworkers to account for the energy loss (E) of the projectile in the target[22], the deflection of the projectile atom by Coulomb repulsion (C) from the target atom[20], and the relativistic (R) nature of the target electron orbitals themselves[23]. G. Lapicki and A. Zander[24] summarized the new theory for K-shell ionization. This approach has also been applied to the OBKN theory by Lapicki[25] and coworkers with much success. The resultant theory (ECPSSR) goes beyond the first Born approximations of the PWBA and OBKN theories and thus have extended the regions of validity from $Z_1/Z_2 \ll 1$ and $v_1/v_e \gg 1$ to $Z_1/Z_2 < 1$ and $v_1/v_e < 1$.

The processes involved in very slow ion-atom collisions have been described by the electron promotion model based on the works of Fano, Lichten, Barat and Lapicki.[26-29] This model has given rise to the Molecular Orbital (MO) Theory. Meyerhof, Anholt and coworkers[30-34] have examined this in detail and have found that for symmetric and near-symmetric ($Z_1 \simeq Z_2$) collisions the theory describes the data trends very well for the resultant K-shell vacancies. They have identified four basic MO interaction regions resulting in K-shell vacancies. Region (i) 1s excitation: These are due primarily to ionization in the united atom for $Z_1 < Z_2$ by a process similar to direct ionization. They result in separated atomic K-shell vacancies. Region (ii) 2p excitation: These may be due to a direct excitation process from the 2pσ level or a two step coupling process from the 2pσ to the 2pπ and finally to the 3pπ leaving a vacancy in the K-shell of the separated atom. Region (iii)

K-vacancy sharing: The $2p\sigma$ vacancies created by some process (possibly in region (ii) above) are then shared between the heavy and light atoms in the collision as they separate in the outgoing phase of the collision. This results in K-shell vacancies in the separated atom. Region (iv) K-L level matching: For asymmetric collisions, a $3d\sigma$ molecular orbital vacancy produced by some means can be shared between the 1s (K-shell) level of the light atom and the 2p (L-shell) level of the heavy atom. This would result in both K- and L-shell vacancies but our investigation would probably be concerned with the L-shell vacancy of the heavy atom. These vacancies are enhanced in thick targets as multiple collisions will give rise to more $2p\sigma$ and $3d\sigma$ vacancies which can be transferred to separated atom K-shell vacancies by processes described in regions (iii) and (iv) above. The effects of these vacancies upon higher level (L- and M-shell) vacancies in the separated atom are still not clear.

This investigation is an attempt to bridge the gap between the DI plus EC regions and the electron promotion region by examining collisions in the $Z_1 < Z_2$ low velocity interaction. The data are compared to the ECPSSR theory in an attempt to push it to the limits of its validity.

Experimental X-ray Production Measurements

Since early in this century, x-ray production by charged particle ionization has been studied very extensively. The results of these investigations have been reported in numerous publications. Experimental cross section results have been a major portion of these papers. Most cross section results have been tabulated in summary reports. Some excellent published summaries include:

(a) Gardner and Gray[35] for K-shell work prior to 1978,
(b) Paul and Muhr[36] for K-shell work prior to 1983,
(c) Hardt and Watson[37] for L-shell work prior to 1976,
(d) T. J. Gray[38] for L-shell work prior to 1977,
(e) Sokhi and Crumpton[39] for L-shell work prior to 1983 with incident protons, and
(f) G. Lapicki, _et. al._[40] for L-shell work prior to 1985 with incident helium ions.

In addition to these summaries, numerous other results of inner-shell ionization cross-section measurements have been reported in the literature. Other results and references for K-shell ionization measurements can be found in references 41 to 49. More results and references for L-shell ionization measurements can be found in a recent paper by Andrews _et. al._[50] M-shell ionization results with references to previous work can be found in papers by Andrews _et.al._[51] and Mehta _et. al._[52,53] For most of the data reported in these papers the studies were confined to very low Z_1/Z_2 ratios and very high velocity ratios or for $Z_1/Z_2 \approx 1$ and very low velocity ratios.

The scope of the work reported here is to push the

ECPSSR theory into the transition region of low Z_1/Z_2 and low velocity ratios. For incident ${}^9_4Be^+$ ions with energies ranging from 0.5 to 2.5 MeV (55 keV/amu to 280 keV/amu) the experiments examined the following regions:

(i) $0.21 \leq Z_1/Z_2 \leq 0.44$, $0.092 \leq v_1/v_{2K} \leq 0.47$ for the K-shell studies,

(ii) $0.087 \leq Z_1/Z_2 \leq 0.142$, $0.027 \leq v_1/v_{2L} \leq 0.151$ for the L-shell studies,

(iii) $0.048 \leq Z_1/Z_2 \leq 0.068$, $0.022 \leq v_1/v_{2M} \leq 0.101$ for the M-shell studies.

The targets used in this study ranged from ${}_9F$ to ${}_{19}K$ for the K-shell, ${}_{29}Cu$ to ${}_{40}Zr$ for the L-shell, and ${}_{59}Pr$ to ${}_{83}Bi$ for the M-shell measurements.

Experimental Difficulties

There are a few experimental reasons why the study presented here has not been done before. The production of a sufficient ${}^9Be^+$ beam is difficult for a low-medium energy 2.5 MV Van de Graaff accelerator. The equipment used to produce this ion beam is described in Chapter III. The energies of the x-rays for the elements under study all are less than 3.5 keV. The resulting uncertainty in efficiency determination is due in large part to the rapid decrease in Si(Li) detector efficiency for $E_X < 2$ keV and the presence of the silicon and gold absorption edges. The method used to determine detector efficiency is also described in

Chapter III. For the L- and M-shell studies on thin targets, problems may arise due to the evaporation of the target elements on thin carbon backings which may have low Z contaminant elements on them. These contaminants introduce additional peaks in the x-ray spectra which tend to obscure the L- or M-shell x-rays of interest. This problem was minimized by using techniques of evaporation reported in earlier papers.[53,54]

The resultant data were compared to the ECPSSR theory for total ionization by converting the total ionization cross sections to x-ray production cross sections using the single hole fluorescence yields of Krause.[55] There is a problem using this method due to multiple ionizations in the target which will change the fluorescence yields. Multiple ionizations also cause a shifting in the actual x-ray line energies causing further uncertainty in the detector efficiencies. These problems will be discussed further in Chapters IV and V.

CHAPTER II

THEORY

There have been numerous theories developed in order to describe inner-shell vacancy production by incident charged particles. Some of these theories include the Binary Encounter Approximation (BEA),[1,2,3] the Semi-Classical Approximation (SCA),[4,5] and the Electron Promotion[26-29] (Molecular Orbital, MO)[30-34] theory. The two theories used for comparison with the measurements reported here are the First Born Approximation and the Perturbed Stationary State (PSS) theory. These two theories describe the vacancy production by two major processes, the Direct Ionization (DI) and Electron Capture (EC) processes.

First Born

Plane Wave Approximation

The First Born theory is a quantum mechanical description of vacancy production which uses a perturbation technique and incorporates contributions from two major processes. The Plane Wave Born Approximation (PWBA) is that part of the theory which describes the Direct Ionization process while the Oppenheimer-Brinkman-Kramers treatment of Nikolaev describes the electron capture process.

The PWBA theory was first developed by Bethe[6] in 1930. It assumes a high incident velocity for the projectile ($Z_1 e^2/hv_1 << 1$) and a very low Z_1/Z_2 ratio. These conditions were necessary in order to easily evaluate the transition matrix element integrals which when squared give an expression for the cross section. The high velocity limit is required to describe the incident ion in simple terms (i.e., a plane wave) and the low Z_1/Z_2 ratio insures a small interaction between the ion and atomic electron so that the perturbation calculation remains valid. The expression for the cross section is given by:

$$\sigma^{DI} = \left(\frac{m}{2\pi\hbar^2} \right) \left\langle \Phi_f(\vec{r}_1)\, \Psi_f(\vec{r}_2) \left| \frac{1}{\vec{r}_1 - \vec{r}_2} \right| \Phi_i(\vec{r}_1)\, \Psi_i(\vec{r}_2) \right\rangle \qquad \text{(II-1)}$$

where Φ_i and Φ_f are the incident and final state wave function of the projectile described by plane waves, Ψ_i and Ψ_f are the initial and final state wave functions of the target atomic electron, usually described by hydrogenic and spherically scattered wave functions, and $\vec{r}_1 - \vec{r}_2$ is the separation between the projectile and the target electron.

Using ΔE and $\hbar q$ as the energy and momentum transfered to the ionized electron, the resulting differential cross section for Direct Ionization to the continuum using a hydrogenic wave function for the electron is given by

$$d^2\sigma^{DI}_{W,n} = 8\pi a_0 \left[\frac{Z_1 e^2}{Z_{2S}\hbar v_1}\right]^2 \left|F_{W,n}(Q)\right|^2 \frac{dW\,dQ}{Q} \qquad \text{(II-2)}$$

where a_0 is the hydrogen Bohr radius and v_1 is the relative velocity between the projectile and target electron ($v_1^2 = 2E_1/M_1$). The energy and momentum transfered during the collision are given as

$$\Delta E = W \cdot Z_{2S} \cdot Ry \qquad \text{(II-3)}$$

and

$$\hbar q = Q^{\frac{1}{2}} \cdot Z_{2S} \Big/ a_0 \qquad \text{(II-4)}$$

Ry is the Rydberg constant which is 13.6 electron volts. The screened nuclear charge, Z_{2S}, is given by Slater[56] to be

$$Z_{2S} = \begin{cases} Z_2 - 0.3 \text{ for the K-shell} \\ Z_2 - 4.15 \text{ for the L-shell} \\ Z_2 - 11.25 \text{ for the } M_1,\ M_2, \text{ and } M_3 \text{ subshells} \\ Z_2 - 21.15 \text{ for } M_4 \text{ and } M_5 \text{ subshells.} \end{cases} \qquad \text{(II-5)}$$

$|F_{W,n}(Q)|^2$ is defined by Merzbacher and Lewis,[7] Walske,[8] and Choi[10] using the dimensionless energy and momentum transfer parameters. Roughly this term can be expressed as

$$\left|F_{W,n}(Q)\right|^2 = \frac{2^7 Q \exp\left\{-\left(\frac{2\pi}{k}\right)\arctan\left[\frac{2k}{n}\left(Q - k^2 + \frac{1}{n^2}\right)\right]\right\}}{n^3\left[1 - \exp\left(-\frac{2\pi}{k}\right)\right]\left[\left(Q - k^2 + \frac{1}{n^2}\right)^2 + \frac{4k^2}{n^2}\right]^3} \cdot C_n' \qquad \text{(II-6)}$$

with n = 1,2, or 3 for K-, L-, or M-shell ionization respectively and $k^2 = W - 1$. C_n' is a series of terms involving k, Q and other constants derived in the above papers (ref. 7,8,9 and 10) for the different inner-shell ionizations.

By integrating II-2 over the dimensionless momentum dQ, one obtains the excitation function, $I_n(W)$, for the ionziation. This in turn is to be integrated over the dimensionless energy dW to yield the total ionziation cross section. The "atomic form factor" is:

$$F_{n,\ell}\left(\eta_i/\theta_i^2\, , \theta_i\right) = \int_{\theta_i/n}^{\infty} dW \int_{W^2/4\eta_i}^{\infty} \frac{dQ}{Q} \left| F_{W,n}(Q) \right|^2 \qquad \text{(II-7)}$$

where η_i is the reduced velocity parameter, $\eta_i = [v_1/(Z_{2s} v_0)]^2$, and θ_i is the scaled binding energy (or screening number), $\theta_i = (\hbar\omega)_i n^2/Z_{2s}^2 R_y$, $(h\omega)_i$ is the observed binding energy of the i^{th} electron. The final cross section for Direct Ionziation of the i^{th} target atomic shell is then

$$\sigma_i^{DI} = \sigma_0 Z_{2i}^{-4} \theta_i^{-1} F_{n,\ell}(\eta_i/\theta_i^2 , \theta_i) \qquad \text{(II-8)}$$

where $\sigma_0 = 8\pi a_0 \cdot Z_1^2$ and $F_{n,\ell}(\eta_i/\theta_i^2 , \theta_i) = \frac{(2j+1)}{2(2\ell+1)} \frac{\theta_i}{\eta_i} f_i(\eta_i , \theta_i)$ is the atomic form factor. These form factors have been calculated and tabulated previously.[57-60] The final form may then be written as

$$\sigma_i^{DI} = \sigma_0 Z_{2i}^{-4} \eta_i \frac{(2j+1)}{2(2\ell+1)} f_i(\eta_i, \theta_i) \tag{II-9}$$

Oppenheimer-Brinkman-Kramers-Nikolaev Treatment

Once the projectile has penetrated the inner-shells of the target atom, there is a possibility that another process other than Direct Ionization can occur. This process is a rearrangement collision where the electron in the target atom is attracted to and is captured by the penetrating ion. This electron capture (EC) process was first analyzed by Oppenheimer[17] in 1928. Brinkman and Kramers[18] (1930) evaluated this process by a Born Approximation technique including two perturbing potentials, (i) the Coulomb attraction between the target atom and its electron and (ii) the attraction between the incident ion and the target electron. Jackson and Schiff[61] (1953) showed that the Coulomb repulsion between the incident and target nuclei needed to be included. In 1966, Nikolaev[19] incorporated Jackson and Schiff's term with observed binding energies and non-relativistic, screened hydrogenic wave functions in his cross section calculations.

The Schroedinger equation Hamiltonian of the capture interaction is written as

$$-\frac{\hbar^2}{2M_1}\nabla_R^2 - \frac{\hbar^2}{2\mu_2}\nabla_{r_2}^2 + V(\vec{r}_1) + V(\vec{r}_2) + U(\vec{R}) \qquad \text{(II-10)}$$

for the time before the collision. After the collision the Hamiltonian is given by equation II-11.

$$-\frac{\hbar^2}{2M_2}\nabla_R^2 - \frac{\hbar^2}{2\mu_1}\nabla_{r_1}^2 + V(\vec{r}_1) + V(\vec{r}_2) + U(\vec{R}) \qquad \text{(II-11)}$$

where $\mu_1 = mM_1/(m + M_1)$, $M_1 = M_1(m + M_2)/(m + M_1 + M_2)$, $\mu_2 = mM_2/(m + M_2)$, and $M_2 = M_2(m + M_1)/(m + M_1 + M_2)$. $\vec{r}_1$ and $\vec{r}_2$ are the position vectors for the incident and target nuclei of masses M_1 and M_2 to the target (captured) electron. $\vec{R}$ is the distance between M_1 and M_2. With the interaction potentials being given as:

$$V(\vec{r}_1) = \frac{Z_1 e^2}{|\vec{r}_1|}, \quad V(\vec{r}_2) = \frac{Z_2 e^2}{|\vec{r}_2|}, \quad \text{and} \quad U(\vec{R}) = \frac{Z_1 Z_2 e^2}{|\vec{R}|}, \qquad \text{(II-12)}$$

then the total cross section for electron capture from the i^{th} state of the target to the f^{th} state of the projectile is

$$\sigma_{if}^{OBKN} = \frac{1}{(2\pi\hbar^2)^2}\left[\frac{M_1 M_2}{M_1 + M_2}\right]\frac{v'}{v}\left|\langle f|U|i\rangle\right|^2, \qquad \text{(II-13)}$$

where $\langle f|U|i\rangle$ is the interaction matrix element

$$\left\langle f \middle| U \middle| i \right\rangle = \int e^{-i\vec{k}'\cdot\vec{R}'} \Psi_f^{*}(\vec{r}') \left[V(\vec{r}) + U(\vec{R}) \right] e^{+i\vec{k}\cdot\vec{R}} \Psi_0(\vec{r}) \, d\vec{r} \, d\vec{R} \ , \qquad \text{(II-14)}$$

$\Psi_0(r)$ is the ground state wave function of the electron in the target atom, Z_2, and $\Psi_f(r)$ is the wave function for the electron in the projectile, Z_1. The incident projectile's momentum, position, and velocity parameters are given by the unprimed $\vec{k}$, $\vec{R}$, and $\vec{v}$ variables while the primed variables ($\vec{k}'$, $\vec{R}'$, and $\vec{v}'$) refer to the outgoing parameters for Z_1. The resultant cross section calculated by Nikolaev[19] for electron capture from the S shell to the S' shell is

$$\sigma_{SS'}^{OBKN} = \frac{2^9 \pi}{5} \left(\frac{SS'}{V_1} \right) \left(\frac{V_{1S'}}{V_{2S}} \right)^5 \xi_{SS'}^{10}(\theta_S) \ \frac{\Phi\left((1-\theta_S)\, \xi_{SS'}^{2}(\theta_S) \right)}{\left[1 + (1-\theta_S)\, \xi_{SS'}^{2}(\theta_S) \right]^3} \qquad \text{(II-15)}$$

where

$\theta_S = (\hbar\omega)_S \, n_1^2 / (Z_{2S}^2 \, R_y)$ is the scaled binding energy, (II-16)

$\xi_{SS'}(\theta_S) = V_{2S} / [V_{1S'}^2 + q_{SS'}^2(\theta_S)]$ is a dimensionless velocity, and (II-17)

$q_{SS'}(\theta_S) = \frac{1}{2}[V_1 + (V_{2S}^2 \theta_S - V_{1S'}^2)/V_1]$ is the minimum momentum transfered (II-18) in the collision.

The function $\Phi(t)$ given by Nikolaev[19] is

$$\Phi(t) = \frac{5}{t} \left\{ 1 - \frac{4}{t} \left[\left(1 + \frac{1}{t}\right)^3 \ln(1+t) - \left(1 - \frac{1}{t}\right)^2 - \frac{1}{3} - \frac{1}{2}\left(1 + \frac{1}{t}\right) \right] \right\} , \qquad \text{(II-19)}$$

which, for t < 3, reduces to a good approximation (within

2%):

$$\Phi(t) \doteq (1 + 0.3\, t)^{-1} \qquad \text{(II-20)}$$

Perturbed Stationary State Theory and Other Modifications

Polarization and Binding Effects

For high velocity projectiles, the PWBA theory has historically been validated by experiment.[7,11-16,35,44,46] There is little electron capture present since the incident velocity is much higher than the target electron velocity. However, this process becomes more important as one gets closer to $v_1 \simeq v_e$, and in some cases it can dominate the ionization process for high Z_1 and for highly ionized projectiles (K-shell vacancies in the incident ion). There has been some investigation into the processes limiting the First Born theories to high velocities.[11-16,44,46,59,60] Modifications to this theory have been proposed to account for the low velocity discrepancies.

The Perturbed Stationary State (PSS) formalism of Basbas et. al.[11,12,13] evaluates the effect of a slower ion's presence on the electron orbitals of the target atom. He accounts for the increased binding of the target electron due to the presence of the projectile inside its orbit. The polarization of the electron's orbital caused by a large impact parameter projectile outside the orbital is also accounted for. These effects can be incorporated in the theory by using perturbed electronic wave functions for Ψ_i and Ψ_f in equation (II-1).

These effects have also been accounted for by modifying the PWBA cross section with "perturbations" on the screening parameter, θ_s. These modifications are equivalent to the PSS wave function perturbation. To account for increased binding for small impact parameters, θ_s is modified to be[16]

$$\epsilon_s \theta_s = \epsilon_s(\xi_s)\theta_s = \left[1 + 2\left(Z_1/Z_{2s}\theta_s\right) g_s(\xi_s)\right]\theta_s \quad , \qquad \text{(II-21)}$$

where $g(\xi_s)$ is obtained by a numerical integration method devised by Hansen.[16] The net effect is seen to cause an increase in the binding of the electron and thus a lower cross section for ionization.

The polarization factor is also incorporated into the PWBA by modifying the screening parameter. First, the effect is studied by assuming that the electron in its orbit may be treated as an isotropic harmonic oscillator and the perturbing potential is Coulombic but expressed as a multipole expansion. For large impact parameters, the dipole and quadrapole terms contribute Z_1^2 and Z_1^3 factors to the transition probability. With this incorporated into the theory, the total screening parameter modification for both polarization and binding effects is[11,21] $\zeta_s \theta_s$, where

$$\zeta_s(\xi_s, C_s) = 1 + \left\{ \frac{2Z_1}{\theta_s Z_{2s}} \left[g(\xi_s, C_s) - h(\xi_s, C_s) \right] \right\} \quad , \text{(II-22)}$$

and $g(\xi_s, C_s)$ and $h(\xi_s, C_s)$ are functions which are derived and discussed by Basbas <u>et al</u>[21] in order to describe the binding and polarization effects respectively. The g function is seen to increase binding thus reducing the cross section while the h function decreases the binding resulting in a slight increase in the ionization cross section. The net effect is evaluated by Basbas <u>et al</u>[11,21] to give the new theory, PSS, in terms of the old PWBA (Equation II-8) as

$$\sigma_i^{PSS} = \frac{\sigma_0}{Z_{2i}^4 \zeta_i \theta_i} \; F_i\left[\eta_i / (\zeta_i \theta_i)^2 \, , \zeta_i \theta_i \right] \quad \text{(II-23)}$$

Coulomb Deflection Effect

In all the treatments for ion-atom collisions using standard Born approximation techniques, the projectile is described by a plane wave (used in the PWBA and PSS theories) or as having a straight line trajectory (SCA). These approximations become invalid for lower velocity incident ions since the plane wave (PWBA and PSS theories) becomes appreciably distorted due to the Coulombic influence of the target nucleus, or the trajectory deviates from the straight line (SCA theory) to a hyperbolic path. Therefore, in order to "stretch" the PSS theory below its high velocity limits, Φ_i and Φ_f (Equation II-1) will have to be altered to account for the presence of a perturbing field; or the nuclear-nuclear interaction can be incorporated as a perturbation potential upon the original plane waves.

Bang and Hansten[4] originally used classical trajectories to account for this effect. Brandt and coworkers[22,23] incorporated an empirical approach to extract an approximate correction factor to the PWBA or PSS theories. This factor was then derived by Lapicki and Losonsky[62] to give support to the result of Brandt. The correction factor can be incorporated into the quantum mechanical treatment (PWBA or PSS) of ion-atom collisions as

$$C_i = (n_i - 1)\ E_{n_i}(\pi d q_i)\ , \qquad \text{(II-24)}$$

where $d = \frac{1}{2}(2\ Z_1 Z_2 e^2 / M_1 v_1^2)$ and $\pi d q_i = \frac{1}{2}\ Z_1 (m/M_1)\ \theta_i^2\ (\eta_i / \theta_i^2)$. d is the half distance of closest approach and $E_{n_i}(\pi d q_i)$ is an exponential integral of order n

$$E_{n_i}(x) = \int_1^\infty t^{-n_i} e^{-xt}\, dt \doteq \frac{(n_i - 1)}{(n_i - 1 + x)}\ e^{-x} \quad . \qquad \text{(II-25)}$$

This correction for the trajectory deflection will tend to reduce the predictions of the PWBA and the PSS theories. This factor is still under considerable study[45,47] as the actual effect at very low velocities is uncertain. Discrepancies between actual results and theoretical predictions at low velocities may be due to uncertainties in this factor. The total correction is incorporated the following factor

$$\sigma_i^{CPSS} = C_i \ \sigma_i^{PSS} \quad . \tag{II-26}$$

Relativistic Correction

At low incident velocities, the ionization process involves the target's high velocity electrons in order to conserve momentum during the interaction. Several methods have been suggested to account for the relativistic effects upon the ionization. Jamnik and Zupanicic[14] as well as Davidovic *et al*[63] used relativistic wave functions in the quantum mechanical theories but the calculation is long and difficult. Merzbacher and Lewis[7] modified the screening parameter, Anholt[64] derived a semi-empirical method, while Brandt and Lapicki[23] proposed a method to modify the velocity dependent parameter η_i,

$$\eta_i^R = m_i^R(\xi_i)\eta_i = \left[(1 + 1.1 y_i)^{\frac{1}{2}} + y_i\right] \eta_i \ , \tag{II-27}$$

where $m_i^R(\xi_i)$ is a relativistic correction factor (equivalent to the relativistic mass) derived by Brandt and

Lapicki[23] based upon a fitting parameter y_i:

$$y_i = 0.40(Z_{2i} / 137)^2 \Big/ \xi_i(\theta_i) \quad . \qquad \text{(II-28)}$$

Correcting for relativistic effects in this manner has been shown to slightly increase the ionization cross section for low velocity interactions.[23]

Modification to Electron Capture Cross Section

Modification of the Electron Capture (EC) contribution to the total ionization was studied by Lapicki and McDaniel[25] in 1980. The corrections for the polarization and binding effects are incorporated into the EC theory of OBKN by modifying the screening parameter as in the PWBA or PSS theories. The θ_i parameter is changed to be $\zeta_i \theta_i$ as defined by Equation II-22. Likewise the Coulomb deflection correction is incorporated by the multiplicative factor of II-24. The reason for expressing the electron capture contribution in PWBA-PSS formalism is now clear; the correction factors are easy to incorporate into this existing formalism. Finally, the relativistic modification to η_i, by defining the mass of the electron to be m_i^R as in equation II-27, is acceptable within certain limits described by Lapicki and McDaniel.[25] The total corrected cross section due to EC from the ith shell of the target to the sth shell of the projectile is

$$\sigma_{is}^{EC\text{-}PSS}(v_1 << v_{2i}, v_{1s}) = \frac{(n_i - 1)}{[n_i - 1 + \pi d q_{is}(\xi_i \theta_i)]} \sigma_{is}^{OBKN}(\xi_i \theta_i) \ . \qquad \text{(II-29)}$$

CHAPTER III

EXPERIMENTAL PROCEDURE

The experimental measurements associated with this work were performed using the 2.5 MV Van de Graaff accelerator in the Regional Nuclear Physics Laboratory at the North Texas State University (NTSU) Physics Department. The thin targets used in the experiment were prepared in the Sample Preparation room of the NTSU Physics Building. The ion sources used in the accelerator were assembled in the Ion Source Preparation room in the Physics Building.

All x-ray production cross section measurements were determined by measuring the x-ray yield per scattered incident ion. For all the beams used, the cross sections were measured as functions of the ion beam energy and target atomic number. For the $^{9}Be^{+}$ beam, some target thickness dependence of the x-ray production cross sections were determined.

Experimental Arrangement

Ion beams of $^{9}Be^{+}$, $^{12}C^{+}$, $^{14}N^{+}$, $^{27}Al^{+}$, and $^{40}Ar^{+}$ were produced in the Van de Graaff accelerator at NTSU which was manufactured by High Voltage Engineering Corporation. The energies of the ions used in this study range from 0.5 to 2.5 MeV. The $^{14}N^{+}$ and $^{40}Ar^{+}$ beams were produced by leaking small amounts of nitrogen or argon gas into the ion source bottle of the accelerator, ionizing the gas by a radio frequency (RF) exciter, and extracting the ions from the ion source into the accelerating tube by a variable (0 - 2700 volts) high voltage DC power supply located in the terminal of the accelerator. Ion beams of beryllium were obtained by leaking small amounts of helium gas into the ion source bottle and accelerating the resultant $^{4}He^{+}$ ions through the exit canal at the source bottle's base. By having the exit canal made from beryllium metal, atoms of the beryllium were sputtered from the canal and some were ionized in the +1 state. These ions were then focused and accelerated into a usable beam. This method is similar to that reported by Norbeck and York[65] for their nuclear experiments except that we used boron nitride and quartz bushings and did not introduce any beryllium metal or beryllium oxide into the interior of the ion source bottle. Our method ultimately resulted in lower beam currents (2.0 nA) than those reported by Norbeck and York but this was enough beam for the atomic studies reported here. Similar arrangements were used to produce $^{27}Al^{+}$ and $^{12}C^{+}$ beams by using the appropriate metal for the ion source exit canal.

This arrangement was suggested for the production of a boron beam, but since boron is very expensive and not an electrical conductor, a modification of the exit canal would be necessary. A small boron nitride tube was machined and inserted into an outer sleeve made from aluminum. Boron nitride was used because of its availability and relative lack of expense. The aluminum sleeve was necessary since aluminum is an electrical conductor and it would allow the extraction field to be focussed into the canal. The extracted He^+ ions would then sputter the canal material resulting in some boron ions being liberated for formation into an ion beam.

The RF ion source used is diagrammed in Figure 1. The base of the source was secured to the terminal end of the accelerator tube of the Van de Graaff accelerator. The clamping flange secured the exit canal in place and insured that the exit canal was at the electrical potential of the base. The ion source bottle was attached to the ion source base by a pliant material such as vinyl which makes an excellent high vacuum seal yet, as the source heated up, it allowed the bottle and base to expand at different rates without compromising the integrity of the vacuum seal. The probe was the point at which the extraction potential was applied. The voltage ranged from 0 to +2700 volts relative to the ion source base. The exit canals used for the Be, Al, and C beams were constructed with typical dimensions shown in Figure 2. The boron nitride exit canal (diagrammed in Figure 3) has been constructed but as of yet has not been tested.

Figure 1. Radio Frequency Exciter Ion Source for
2.5 MV Van de Graaff Accelerator

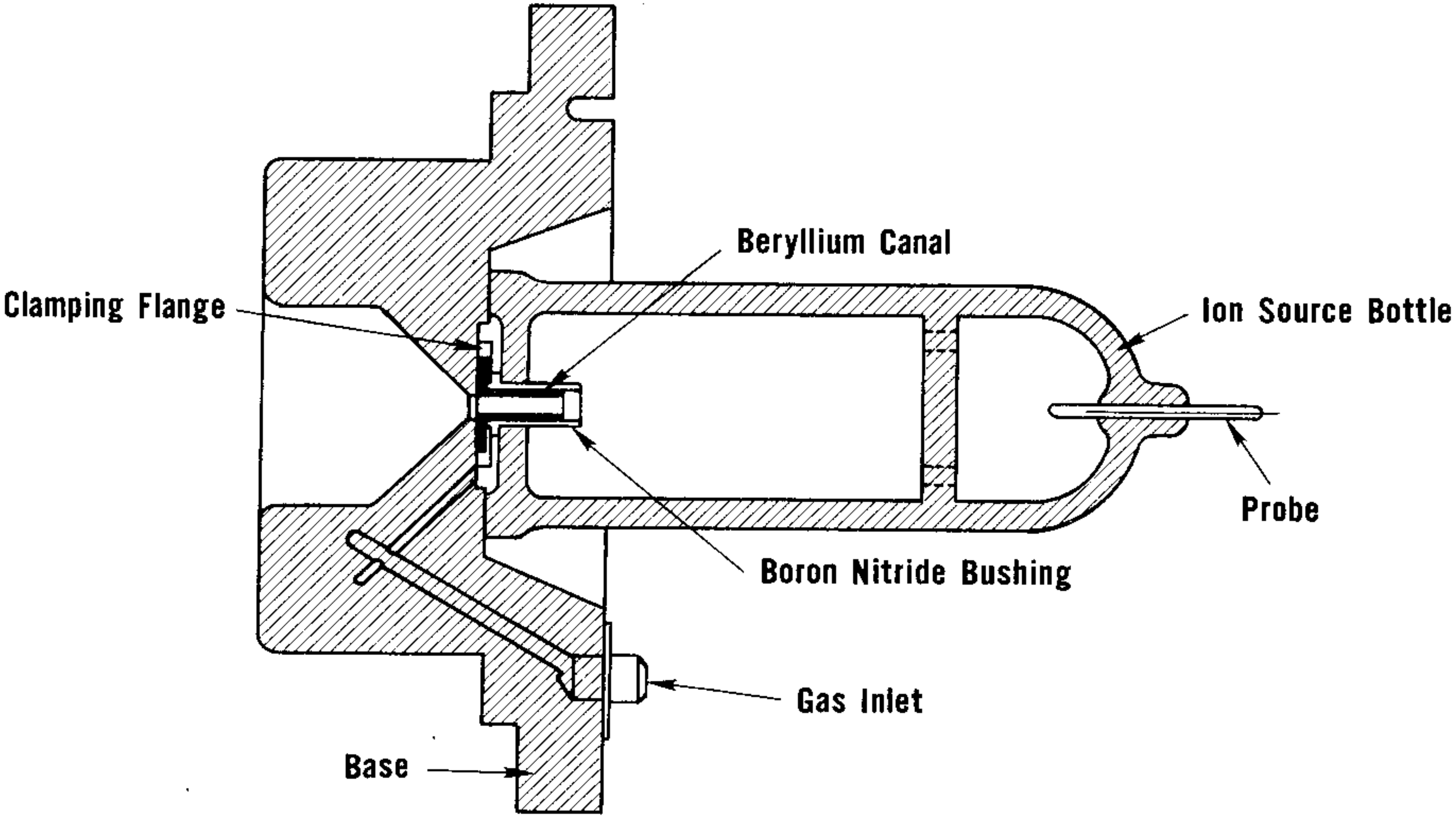

Beryllium Canal
Clamping Flange
Ion Source Bottle
Probe
Boron Nitride Bushing
Gas Inlet
Base

Figure 2. Typical Beryllium Exit Canal for the RF Ion Source

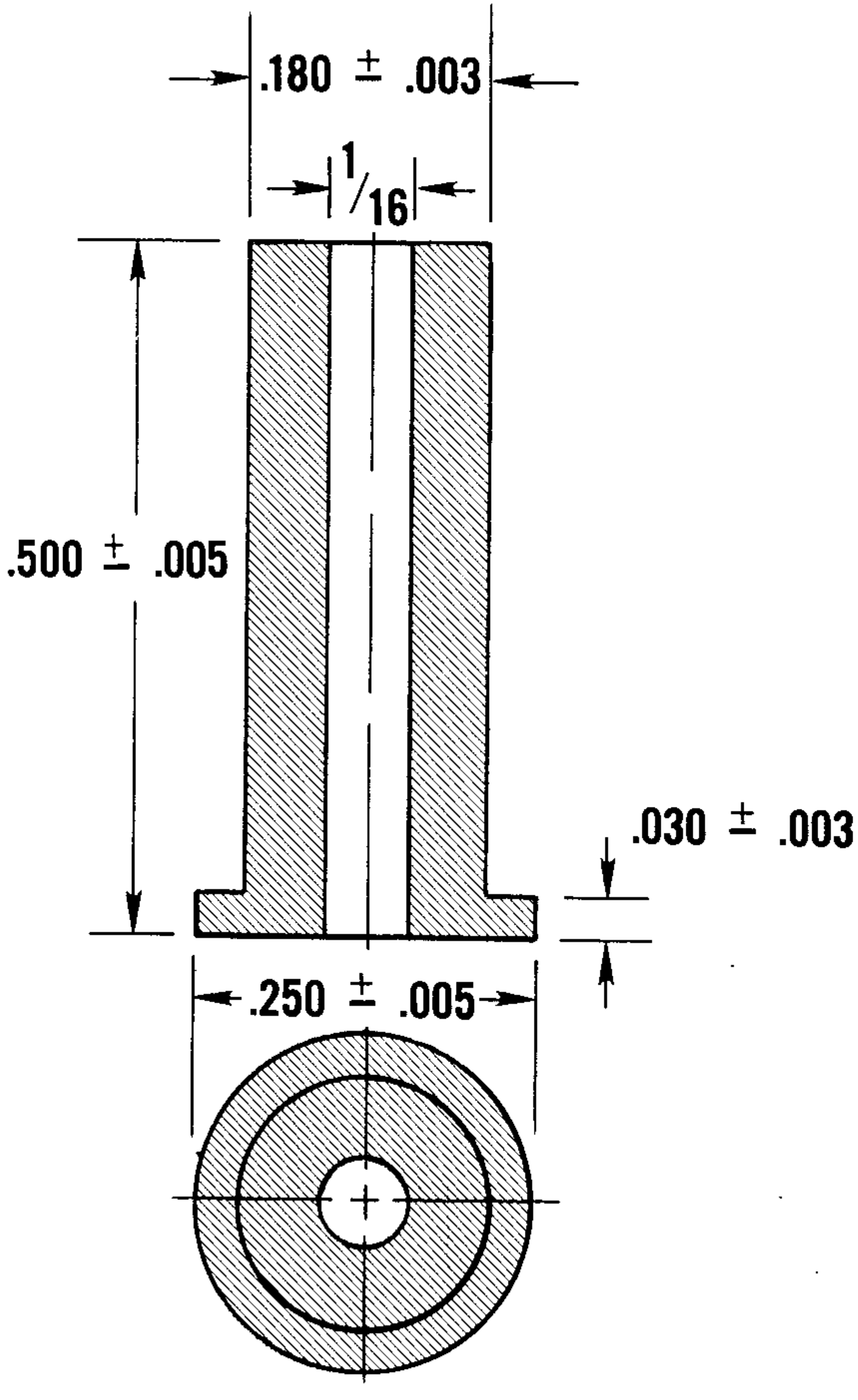

.180 ± .003
1/16
.500 ± .005
.030 ± .003
.250 ± .005

Figure 3. Boron Nitride Exit Canal

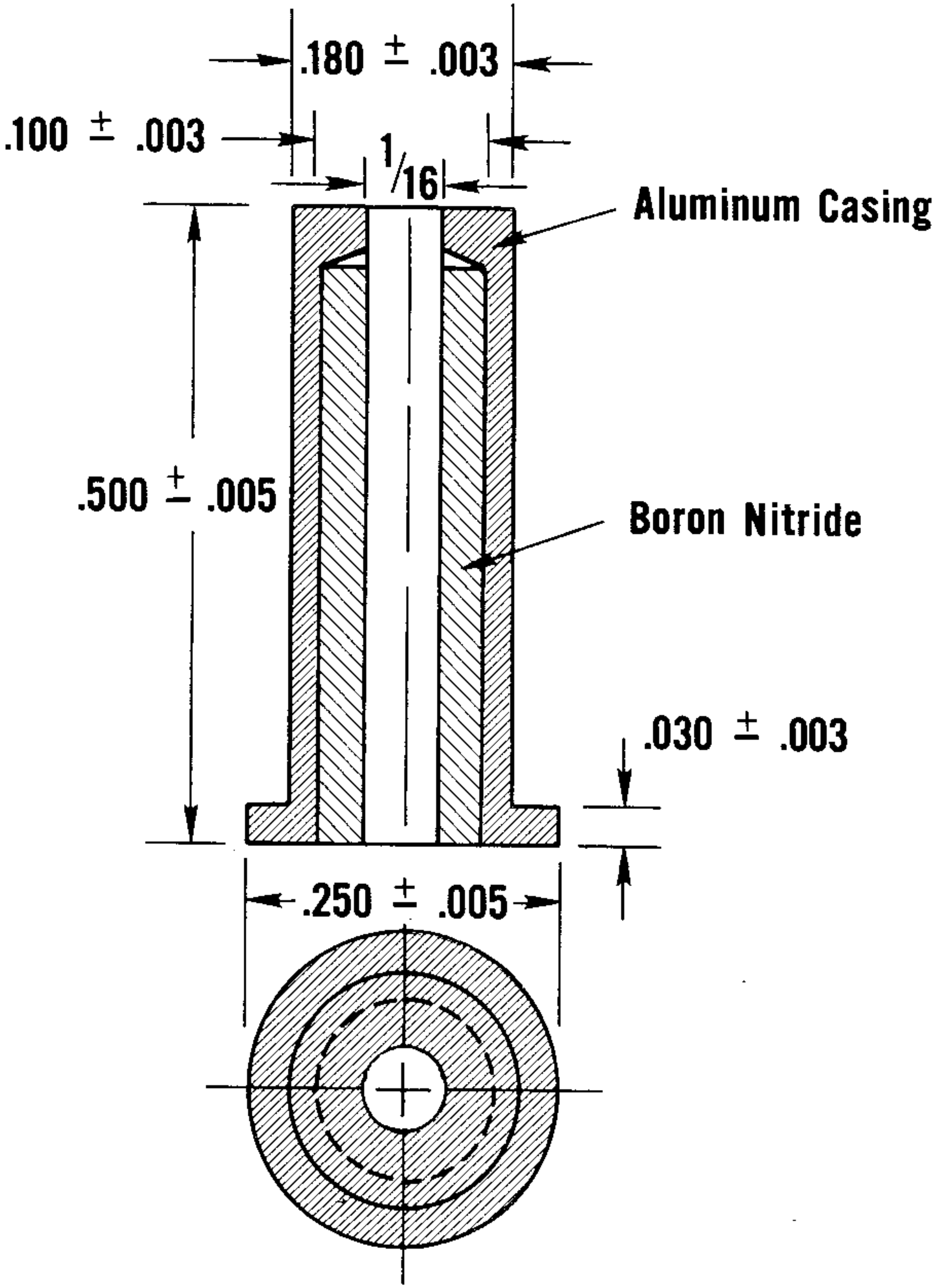

.180 ± .003
.100 ± .003
1/16
Aluminum Casing
.500 ± .005
Boron Nitride
.030 ± .003
.250 ± .005

Figure 4 diagrams the accelerator and the beam line used for these measurements. A four-inch CVC diffusion pump system on the accelerator maintained a pressure of 5.0×10^{-7} torr at the base of the accelerator. The High Voltage Engineering bending magnet (mass-energy product of 500), used for mass-energy analysis of the resultant beam, was maintained at a similar vacuum pressure by a six-inch CVC diffusion pump system. The beam was directed by the bending magnet into the 15° right beam line which was kept at a vacuum less than 1.0×10^{-6} torr by another CVC four-inch diffusion pump.

The beam was re-focussed in the 15° right beam line by a pairs of electrostatic quadrapole focussing lenses. Four pairs of electromagnetic steering coils then directed the beam through the energy control slits and a dual system of collimators into the scattering chamber. The steering magnets were separated by about one meter of flight path. The resultant beam was collimated in two stages. The first pair of collimators encountered were 2 mm diameter holes cut in carbon plates separated by 42 cm with the final collimator about 48 cm. from the front of the scattering chamber. Further collimation was effected by a pair of carbon plates with 1 mm diameter holes separated by 6.4 cm and located at the entrance to the target chamber.

The scattering chamber (Figure 5) used in this experiment was constructed of aluminum and allowed 24

Figure 4. Experimental Arrangement Showing Accelerator and Associated Equipment for Beam Generation and Alignment

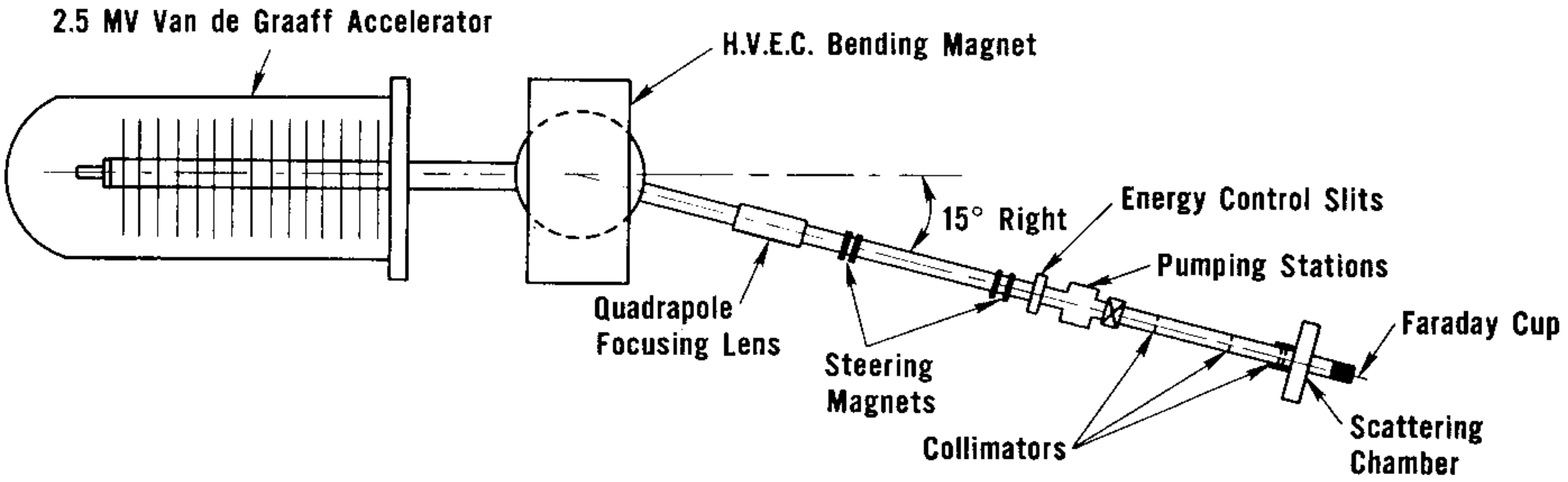
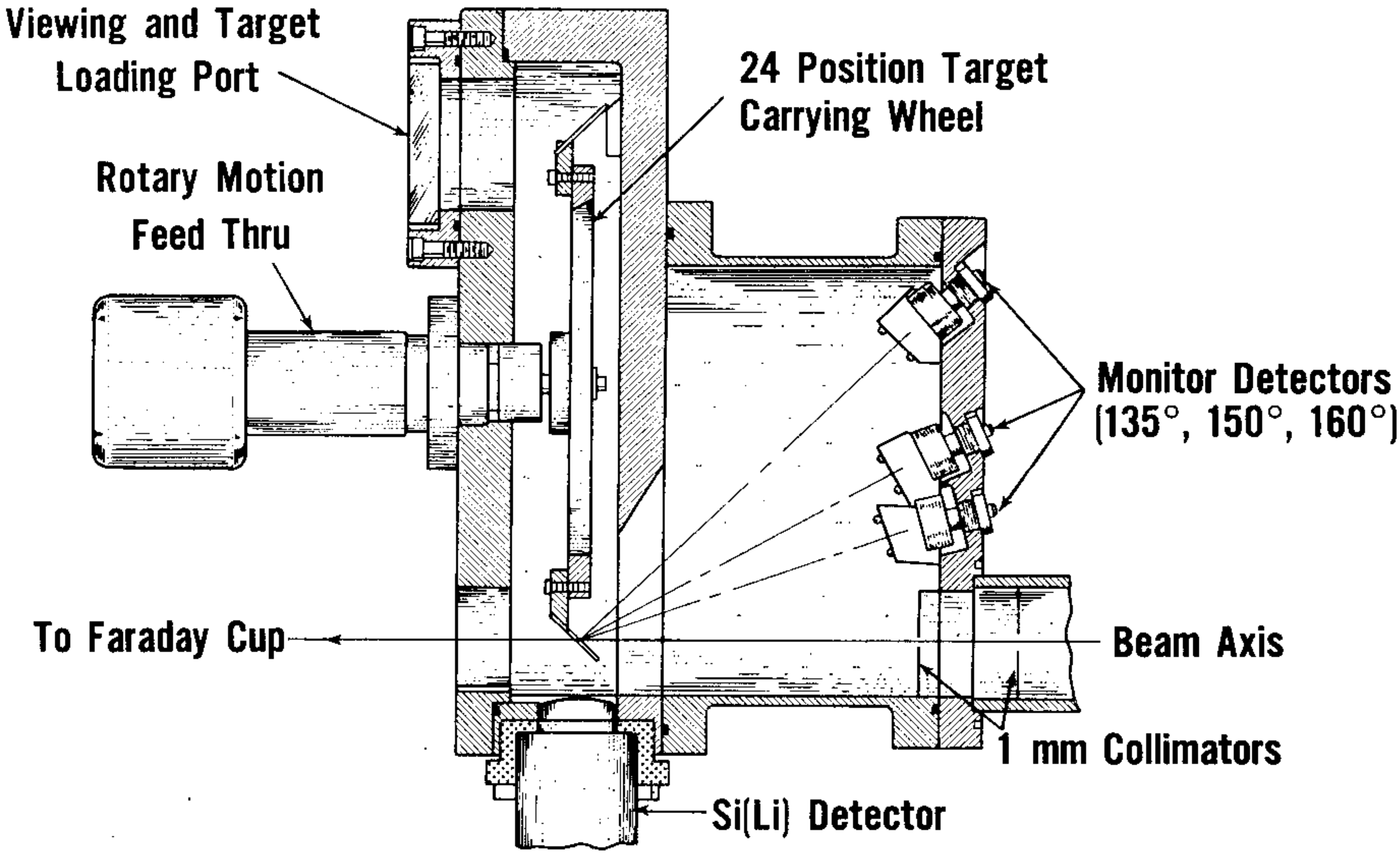

2.5 MV Van de Graaff Accelerator
H.V.E.C. Bending Magnet
15° Right
Energy Control Slits
Pumping Stations
Faraday Cup
Quadrapole Focusing Lens
Steering Magnets
Collimators
Scattering Chamber

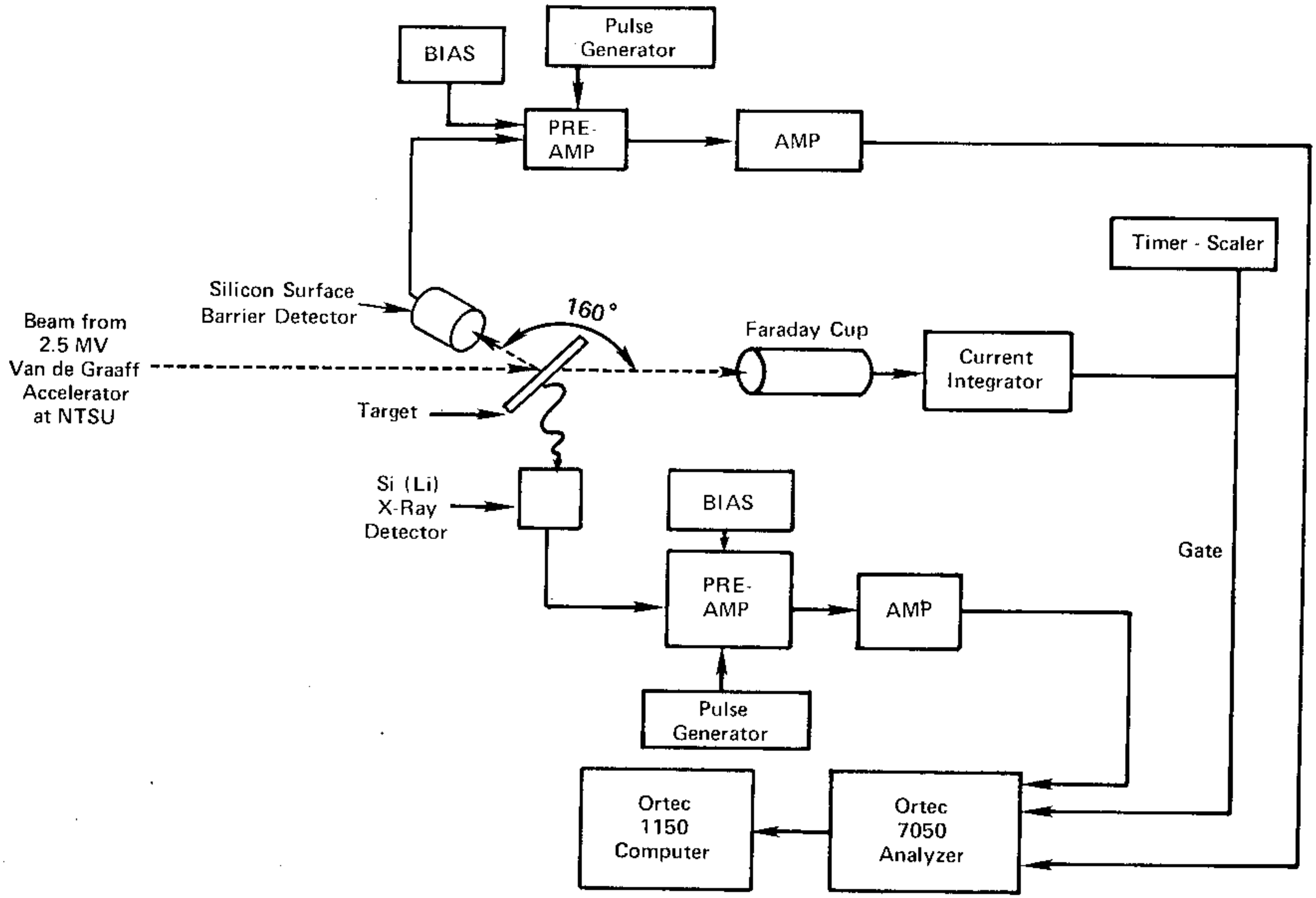
Figure 5. Scattering Chamber Showing Detector Arrangement


Viewing and Target Loading Port
24 Position Target Carrying Wheel
Rotary Motion Feed Thru
Monitor Detectors (135°, 150°, 160°)
To Faraday Cup
Beam Axis
1 mm Collimators
Si(Li) Detector

different targets to be loaded at any one time. Any particular target in the chamber could be rotated into position on the beam axis for analysis at any particular time. The 1 mm. collimators are shown at the entrance to the chamber. Three silicon surface barrier particle detectors were mounted at backscattered angles of 135°, 150°, and 160° with respect to the forward direction of the beam. Most of the measurements for this study were performed using the 160° detector since this gave better scattered energy separation between the peaks in the resultant particle spectrum. The Ortec 7000 series Si(Li) detector system, used to analyze the resultant x-rays from the target, was located below the target at 90° with respect to the forward direction. This detector was placed 4.73 cm. from the beam spot of the target. The target was positioned at a 45° angle with respect to the beam. There was a 7.62 μm thick Be window on the Si(Li) detector and a 3.81 μm Mylar $(C_{10}H_8O_4)_x$ film was stretched across a 4 mm. diameter nylon apperature on top of the detector. This Mylar film reduced the low energy x-rays and Bremsstrahlung thus reducing the dead time in the electronics. The Mylar also prevented scattered ions from penetrating to the active region of the Si(Li) detector.

Figure 6 shows the target arrangement, detectors, and electronics used in this work. The 160° silicon surface

Figure 6. Experimental Electronics System for Signal Analysis

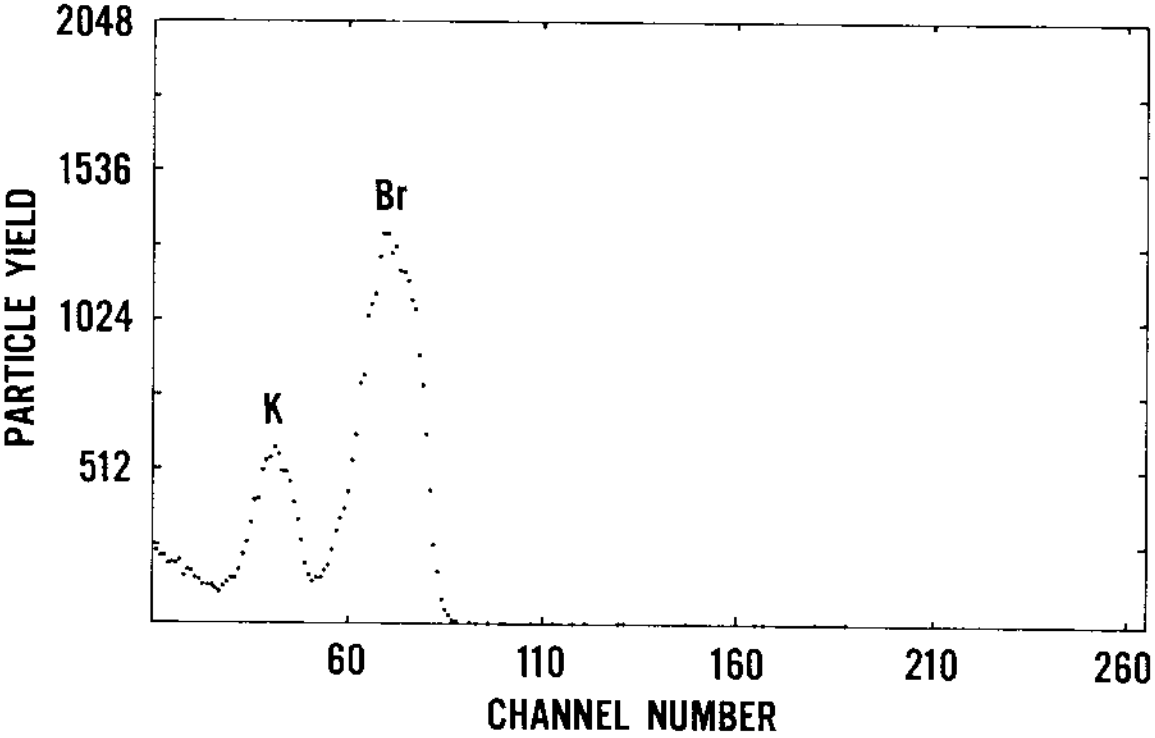

BIAS
Pulse Generator
PRE-AMP
AMP
Timer - Scaler
Silicon Surface Barrier Detector
160°
Faraday Cup
Current Integrator
Beam from 2.5 MV Van de Graaff Accelerator at NTSU
Target
Si (Li) X-Ray Detector
BIAS
PRE-AMP
AMP
Gate
Pulse Generator
Ortec 1150 Computer
Ortec 7050 Analyzer

particle detector was energy calibrated for alpha particles using a ^{244}Cm alpha particle standard (E_α = 5.805 MeV) and a linear Ortec 419 Precision Pulse Generator. The detector solid angle was measured to be 7.454×10^{-4} Sr using the calibrated ^{244}Cm standard. The Full Width at Half Maximum (FWHM) resolution of the particle detector and electronics was determined to be ~20 keV for the ^{244}Cm alpha standard and 14.0 keV for the pulse generator peak. An Ortec 142-A Pre-Amplifier and an Ortec 572 Amplifier prepared the particle energy signal for analysis by Analog-Digital Converter (ADC) number one of an Ortec 7050 Multichannel Analyzer System. Typical particle spectra are shown in Figures 7 and 8.

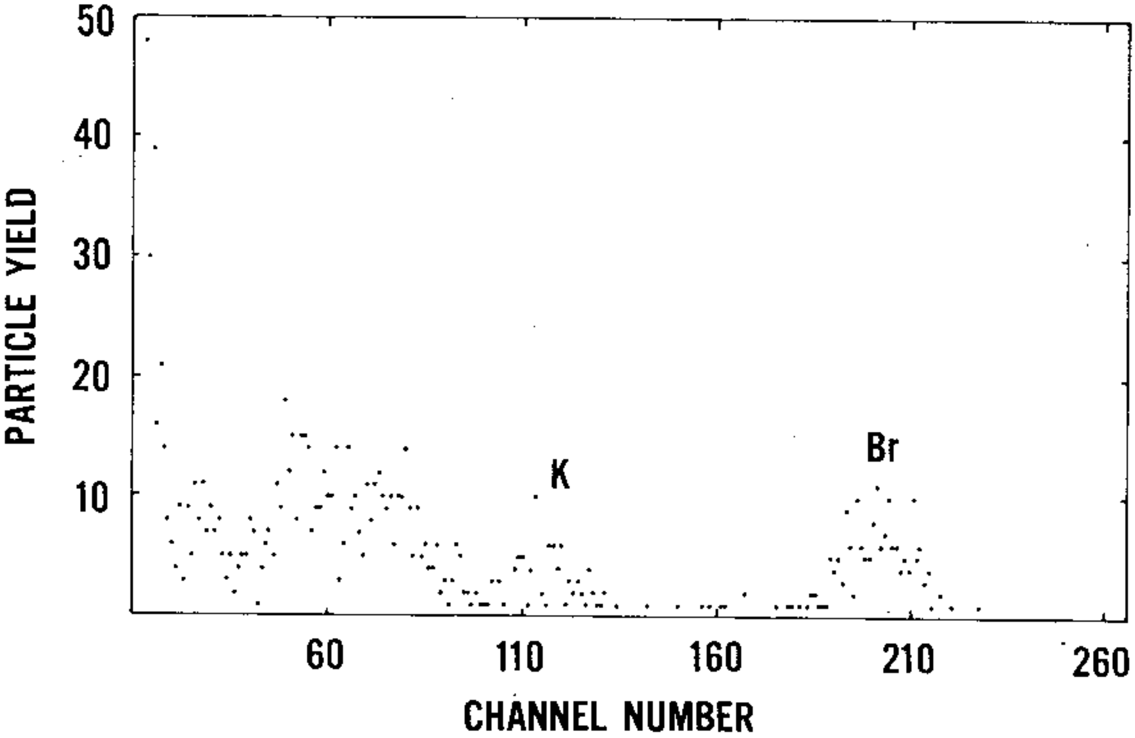
The x-ray spectra were obtained using an Ortec 7000 series Si(Li) detector with an Ortec 117-B Pre-Amplifier. These signals were then amplified by an Ortec 739 Amplifier and fed into the second ADC of the Ortec 7050 analyzer. The pulse generator used in the x-ray energy analysis system was an Ortec 731-A X-ray Energy Identifier. The resolution of the Si(Li) detector system is ~170 eV at the 5.90 keV x-ray of manganese from a ^{55}Fe radioactive source. A sample x-ray spectrum with the associated particle spectrum is shown in Figure 8. Both particle and x-ray spectra were stored on RL01 data disks which were controlled by an Ortec 1150 computer with an RSX-11M operating system.

The incident beam, which passed through the target

Figure 7. Typical Charged Particle Backscatter Spectra for 1.0 and 2.5 MeV Be^+ Ions on a Potassium Bromide Target

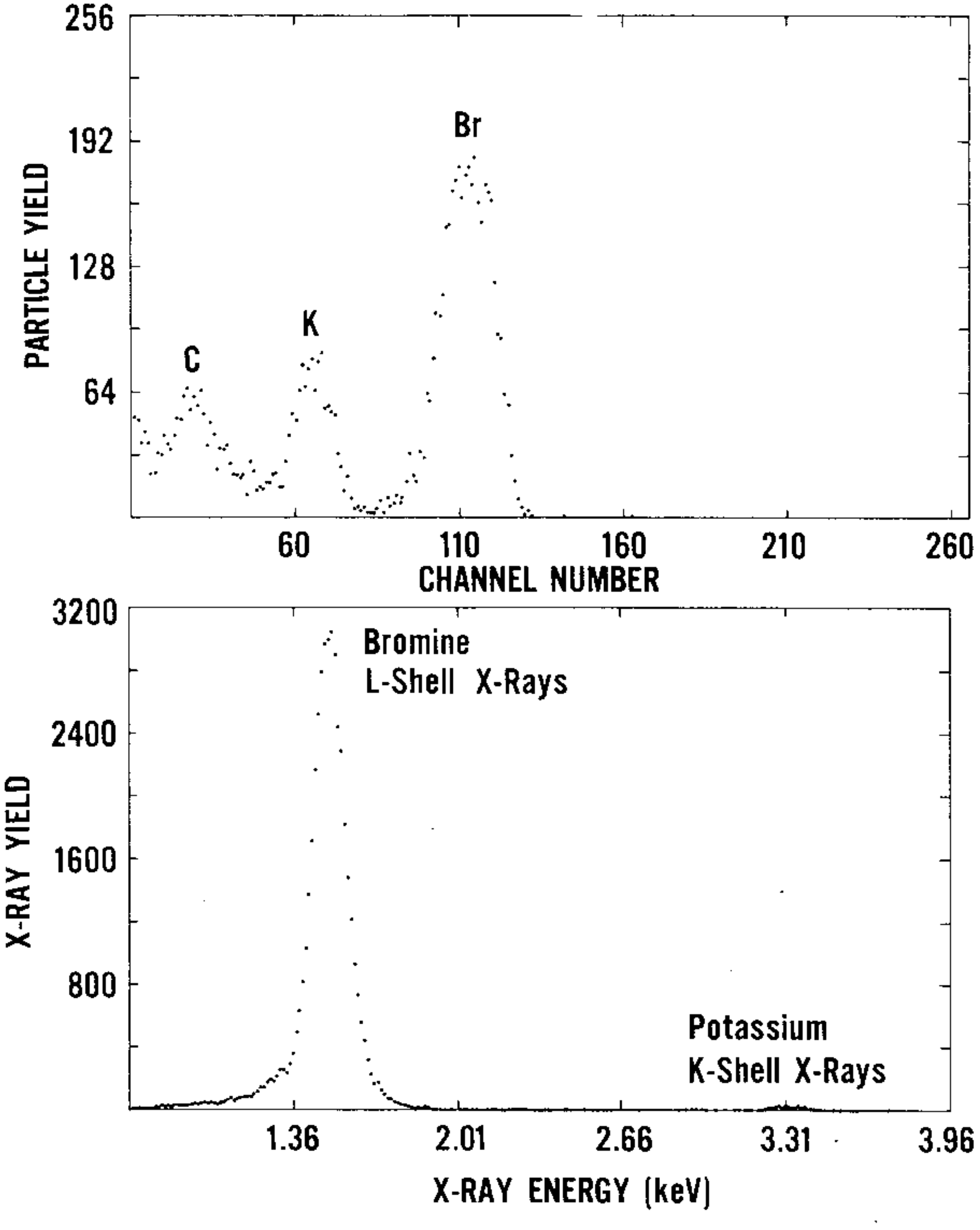


2048
1536
1024
512
PARTICLE YIELD
K
Br
60
110
160
210
260
CHANNEL NUMBER



50
40
30
20
10
PARTICLE YIELD
K
Br
60
110
160
210
260
CHANNEL NUMBER

Figure 8. Typical Simultaneously Measured Charged Particle and X-ray Spectra for 1.5 MeV Be^+ Ions upon a Potassium Bromide Target


256
192
128
64
PARTICLE YIELD
C
K
Br
60
110
160
210
260
CHANNEL NUMBER
3200
2400
1600
800
X-RAY YIELD
Bromine
L-Shell X-Rays
Potassium
K-Shell X-Rays
1.36
2.01
2.66
3.31
3.96
X-RAY ENERGY (keV)

undeflected, was collected in a Faraday cup with a -90 volt electron supressor ring. The collected charge was then passed to a current integrator. Both ADC inputs were gated to start and stop analysis simultaneously with a signal from the current integrator.

Si(Li) Detector Efficiency Determination

In order to measure the absolute x-ray production cross section of an ion-atom collision, the Si(Li) detector must not only be energy calibrated but also its x-ray efficiency (which is energy dependent) must be determined. The absolute efficiency (ε_x) of a Si(Li) detector system for a particular energy x-ray is measured by evaluating the ratio of the number of x-rays detected at that energy per number of such x-rays emitted by the source. This efficiency depends upon two factors: the geometrical arrangement of the detector (G) and the intrinsic peak efficiency (ε_{px}) of the detector arrangement. The relationship is

$$\varepsilon_x = G\,\varepsilon_{px} = \left(\frac{\Omega}{4\pi}\right)\varepsilon_{px} \qquad \text{(III-1)}$$

The geometrical factor is dependent upon the solid angle, Ω, subtended by the detector active area:

$$\Omega = 2\pi\left(1 - \frac{d}{(d^2 + a^2)}\right) \qquad \text{(III-2)}$$

where d is the distance between the source and the detector face and a is the radius of the detector active area. For

$d \gg a$, then

$$\Omega \simeq \frac{\pi a^2}{d^2} \qquad \text{(III-3)}$$

To experimentally determine ε_{px} for the Si(Li) detector at different x-ray energies, one generally measures ε_x and then determines G and calculates the intrinsic efficiency. Since ε_x is the desired factor, then directly measuring this quantity will satisfy the requirements for this study.

The most common method for measuring the absolute efficiency for a Si(Li) detector is to measure the number of photons detected per those emitted by an isotropic standard radioactive source in a known geometry. This method is not suitable for x-rays whose energies lies below 5 keV for two reasons: (1) few reliable radioactive standards exist in this energy range and (2) self absorption of the x-rays in the source increases the uncertainty in the actual number of emitted photons. Since the energies of the x-rays in this study range between 0.67 keV and 3.5 keV, an alternate method of determining ε_x was needed.

Thin targets of $_9F$, $_{11}Na$, $_{12}Mg$, $_{13}Al$, $_{14}Si$, $_{16}S$, $_{17}Cl$, $_{19}K$, $_{20}Ca$, $_{23}V$, $_{25}Mn$, and $_{29}Cu$ were prepared and loaded into the target chamber described earlier. Ion beams of $^1_1H^+$ and $^4_2He^+$ were used to measure the K-shell x-ray yield per incident ion of these targets. By using known values of the x-ray production cross sections from previously measured x-ray production cross sections tabulated by Gardner and Gray[35] or evaluated by the CPSS theory of Basbas[11,12,13,20,21] with the single hole fluorescence yields of Bambynek[66], the absolute efficiencies can be calculated within the uncertainties of the CPSS theory which have been shown to be small.[67,68] Incident ${}^4_2He^+$ beams were used on all targets but ${}^1_1H^+$ beams were used only on the K, V, and Mn targets. For very low Z_2 targets, the particle spectrum is misleading and difficult to interpret for incident protons since not only is there Rutherford elastic scattering occuring at these energies but also nuclear interactions as well. At 160°, all scattering of incident ${}^4_4He^+$ is Rutherford in nature to within a few percent.

The experimental efficiency of the i^{th} x-ray is given by:

$$\varepsilon_{xi} = \frac{Y_{xi}\ t_x}{Y_R\ t_R}\left(\frac{\Delta\Omega}{\sigma_x}\right)\left(\frac{d\sigma_R}{d\Omega}\right) C_i \qquad \text{(III-4)}$$

where Y_{xi} and Y_R are the K-shell x-ray photopeak and particle detector yields, t_x and t_R are the dead-time corrections to the appropriate detectors, $\Delta\Omega$ is the particle detector solid angle, σ_x is the K-shell x-ray production cross section from Gardner and Gray[35] or the CPSS theory[20,21] for the particular ion and energy used, C_i is the correction to the x-ray and particle yields due to the target thickness, and $(d\sigma_R/d\Omega)$ is the differential Rutherford scattering cross section for scattering angle 160° and incident energy of E_1. Table I lists the

TABLE I

EXPERIMENTAL EFFICIENCY MEASUREMENTS

Element	K-shell X-ray Energy	Efficiency	Uncertainty
$_{9}F$	0.677	1.32×10^{-6}	74%
$_{11}Na$	1.041	6.50×10^{-5}	36%
$_{12}Mg$	1.254	1.44×10^{-4}	44%
$_{13}Al$	1.487	4.33×10^{-4}	36%
$_{14}Si$	1.740	5.18×10^{-4}	31%
$_{16}S$	2.308	3.63×10^{-4}	21%
$_{17}Cl$	2.622	5.10×10^{-4}	27%
$_{19}K$	3.313	5.90×10^{-4}	11%
$_{20}Ca$	3.691	5.64×10^{-4}	15%
$_{23}V$	4.952	5.52×10^{-4}	60%
$_{25}Mn$	5.898	8.56×10^{-4}	41%
$_{29}Cu$	8.047	8.31×10^{-4}	21%

experimentally determined efficiency values.

The theoretical efficiency curve is determined by calculating the photon attenuation of the x-rays through the various layers of materials that lie between the target and the Si(Li) detector active regions. These layers are comprised of a Mylar film (3.81 μm), a beryllium entrance window (7.62 μm), a gold contact layer (0.02 μm), and a silicon dead layer (0.5 μm). The efficiency is then calculated by the attenuation law:

$$\varepsilon_x = \varepsilon_o \exp(-\sum_j \mu_j a_j) \qquad \text{(III-5)}$$

where μ_j is the mass attenuation coefficient for the j^{th} layer of material which has a thickness of a_j. The factor ε_o is the efficiency of the silicon active region in the absence of any attenuation and includes the solid angle subtended. The theoretical values are normalized to a theoretical efficiency for silicon K-shell x-rays which allow the best fit to the experimental points of Table I. The best normalization point is $\varepsilon_{Si} = 4.60 \times 10^4$ with an attenuation factor of 0.5775. This lies within the 15% error bars of the experimental silicon efficiency point. The active region efficiency is then $\varepsilon_o = 7.96 \times 10^4$ and thus the other absolute points can be determined by:

$$\varepsilon_x = (7.96 \times 10^{-4}) \exp(-\sum_j \mu_j a_j) \, . \qquad \text{(III-6)}$$

Figure 9 shows the best fit theoretical efficiency curve with the associated experimental points.

Particle Detector Calibration and Pulse Height Defect

The particle detector which was used to detect the Rutherford scattered ions was a B-series EG&G Ortec charged particle detector. This detector is a surface-barrier diode made with high purity single-crystal silicon. Figure 10 illustrates the typical design of this kind of EG&G Ortec detector. As the charged particle enters the active region of the detector, it loses energy by Coulomb interactions with the nuclei and electrons of the silicon wafer material. The interactions with the electrons result in the creation of electron-hole pairs. These charge pairs are swept apart by the electric field (from the applied bias voltage), and the electron signal is collected at the positive back aluminum electrode then transmitted through the electronics described earlier. The amplitude of the resulting electron signal is proportional to the total energy deposited in the detector material by the collisions between the incident charged particle and the electrons in the silicon active layer. All of the energy deposited in the detector by collisions between the charged particle and the silicon nuclei is lost to this signal development process. The mechanism described here is valid for all

Figure 9. Efficiency for the Si(Li) X-ray Detector Showing Experimentally Measured Values with a Theoretical Fit.

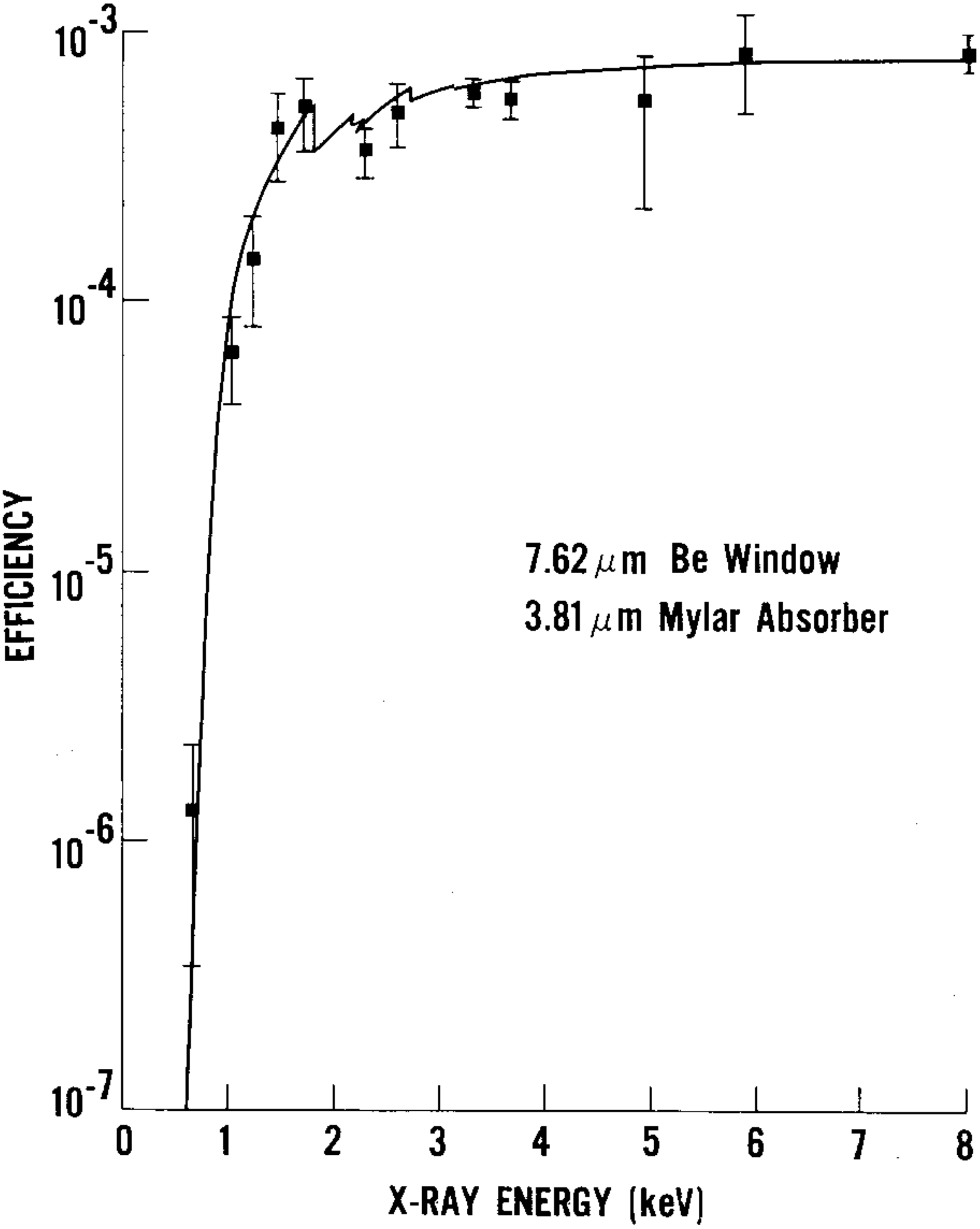
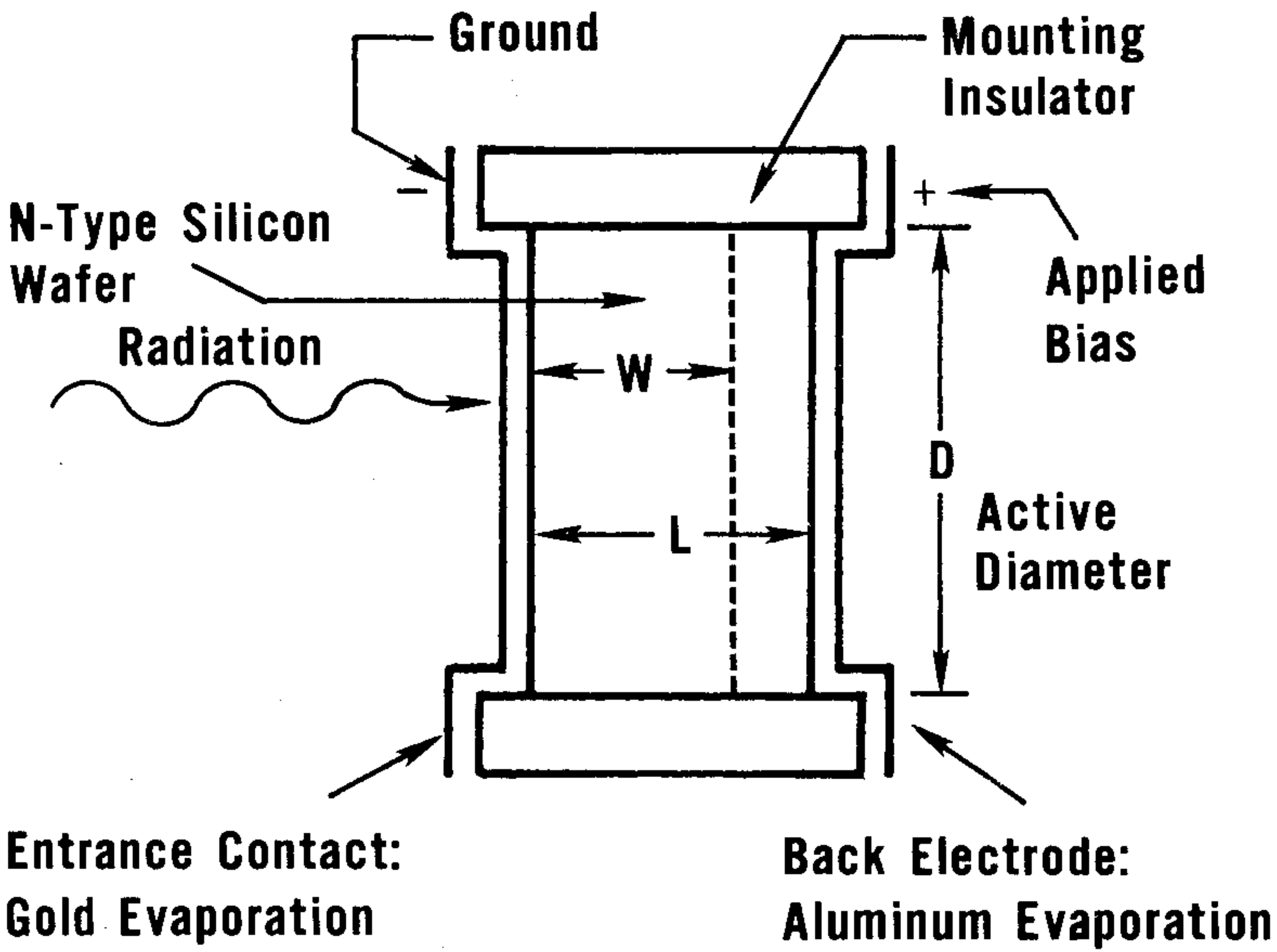

10^-3
10^-4
10^-5
10^-6
10^-7
EFFICIENCY
0
1
2
3
4
5
6
7
8
X-RAY ENERGY (keV)
7.62 μm Be Window
3.81 μm Mylar Absorber

Figure 10. Typical B-Series EG&G Ortec Charged Particle Detector


Ground
Mounting
Insulator
−
+
N-Type Silicon
Wafer
Applied
Bias
Radiation
W
D
Active
Diameter
L
Entrance Contact:
Gold Evaporation
Back Electrode:
Aluminum Evaporation

incident projectiles (protons, alphas, and "heavy ions"). There are, however, other interactions in the detector which become important for heavy particles but which have negligible effects for "light ion" spectroscopy.[70,71] These effects include (i) the entrance window loss effect, (ii) the nuclear collision effect, (iii) plasma formation effects, (iv) channeling effect, and (v) radiation damage effects. These effects yield a different pulse amplitude than normally expected and the cumulative effect is therefore termed the "pulse height defect."

When a charged particle passes through matter, it looses energy. Therefore when the incident particle enters the detector, energy is lost in the gold entrance window. This reduces the total amount of energy available for deposition in the active layer which in turn results in a downward shift in the energy of the photopeak. This effect is greater for high Z ions as compared to low Z ions. Table II lists the energy lost in the gold entrance window of the detector used in our experiment for a 2.0 MeV incident particle. The manufacturer calibrated the gold thickness to be 40 $\mu g/cm^2$ and the stopping powers came from Northcliffe and Schilling.[69] This effect will also contribute to the degradation of the detector resolution because of the statistical fluctuations in the energy loss.

Since the energy transferred from the incident particle to the nuclei of the detector material is lost to the

TABLE II

ENERGY LOST BY 2.0 MeV ION IN 40 μg/cm^2 GOLD ENTRANCE WINDOW OF CHARGED PARTICLE DETECTOR

ION	Stopping Power[69] (keV/mg/cm^2)	Total Energy Lost (keV)
$^{1}_{1}$H	0.046	1.840
$^{4}_{2}$He	0.322	12.88
$^{9}_{4}$Be	0.833	33.32
$^{12}_{6}$C	1.224	48.96
$^{14}_{7}$N	1.372	54.88
$^{27}_{13}$Al	1.425	57.00
$^{40}_{18}$Ar	1.377	55.08

mechanism of electron-hole pair pulse generation, and since the probability of a nuclear interaction increases with decreasing particle velocity, then, for incident particles with the same energy, the heavier ion will lose more energy to the nuclear interactions. This difference can be significant at high energies and for very heavy ions. A heavy ion can lose about 5% of its energy in this process while an alpha particle at the same energy will lose less than 0.1%.[70]

When a charged particle enters a detector the created electron-hole pairs form a plasma cloud. This cloud is normally swept apart by the applied electric field. When heavy ions enter a detector, the resulting plasma cloud is so dense that the applied bias field cannot penetrate it until the cloud becomes sufficiently dispersed by diffusion. This plasma effect has several interesting results. One result is the time delay which is generated between the creation of the charge pairs and the beginning of the rise of the detector pulse.[70,72,73] The rise time of the signal also slows down thus increasing the pulse width.[70,72,73] These two effects of the dense plasma cloud lead to poorer resolution for energy determination. Finally, since the bias field cannot immediately penetrate the plasma cloud, recombination of the charge carriers occurs.[70,71,74,75] The consequence of this recombination is a net loss in signal charge carriers and thus a smaller pulse height.

This particular plasma effect is probably the most dominant effect experienced in the measurements reported in this dissertation. This effect is very difficult to quantify since there is a large dependence upon the applied electric field, the mobility of the charge carriers, and the lifetimes of the carriers in the detector crystal.[71] All these plasma effects will decrease with an increase in the applied bias voltage (increase in the electric field). With a larger electric field, however, charge multiplication effects may cause more problems. A large increase in the electric field may cause electron tunneling which will result in an increase in the leakage current, large signal pulses, high energy tailing, and poor energy resolution.[70] This charge multiplication effect will also lead to detector degradation. The detector used in our experiment had an applied bias field of 10^4 volts/cm which is the recommended value for particle energy spectroscopy.[70]

If a charged particle enters a crystalline solid (such as silicon) along a crystallographic axis, it can be "channeled" along this axis by the surrounding atoms in the crystal lattice. This results in fewer ion-electron collisions per unit length, thus increasing the particle's range. Likewise, nuclear collisions are also reduced in total number. The net consequences of this are better resolution, less dense plasma cloud, and a lower recombination rate.[70] To obtain significant channeling, the particle must enter the detector within 0.5° of the chosen crystalline axis. The B-series detector is cut off-axis to minimize this ion channeling. This insures that light ions (protons, etc.) will come to rest and deposit all their energy in the active region of the detector. Since there is very little capability to precisely orient the detector to maximize channeling, this effect would be of little use in this experiment, anyway.

As the incident charged particle loses energy in the detector, some change in crystal parameters will take place. Some of these crystallographic changes may result in lattice site defects (vacancies and interstitials). These radiation defects are electrically active and consequently cause local variations in the bias field. These variations can result in recombination or charge carrier trapping thus reducing the net pulse height.[70] The most detrimental consequence of the deep electrically active defects is an increase in the detector leakage current which degrades resolution and eventually renders the detector useless.[70]

All the phenomena described above, which lead to a reduction in pulse amplitude, are collectively termed the "pulse height defect." This change in amplitude necessitates calibrating the particle detector for all particles incident upon the detector. The alpha particle calibration was determined by placing a ^{241}Am or ^{244}Cm alpha source at the target position and examining the energy spectrum. By normalizing a pulse generator to the appropriate alpha energy peak, the lower energy calibration points were determined. This calibration was then confirmed by examining different energy alpha particles elastically scattered from selected targets. For heavy ions, the detector was calibrated by obtaining a specific energy heavy-ion beam and examining the energy distribution of the Rutherford scattered particles from specific thin targets. Using the appropriate kinematics, the actual scattered energies are known.

Beams of ^{9}Be, ^{27}Al, and ^{40}Ar were analyzed in this manner and the resultant calibration curves are shown in Figures 11 and 12. The data were fit with straight lines by a least squares method and the slope is given on the figures. The actual trend of the data is probably not linear but this assumption is adequate for our purpose which was to identify particular scattered particle peaks. Notice that the slope of the calibration curves increase with increasing incident projectile mass. This trend plus the slight increase in the full width at half maximum confirms that the resolution for heavy-ion spectroscopy is poorer than that for the light projectiles. The 160° detector was utilized for the beryllium, nitrogen, and carbon ion data while the aluminum and argon ion data were taken using the

Figure 11. Calibration Curve for Charged Particle Detector Showing the Pulse Height Defect for Al^+ and Ar^+ Ions

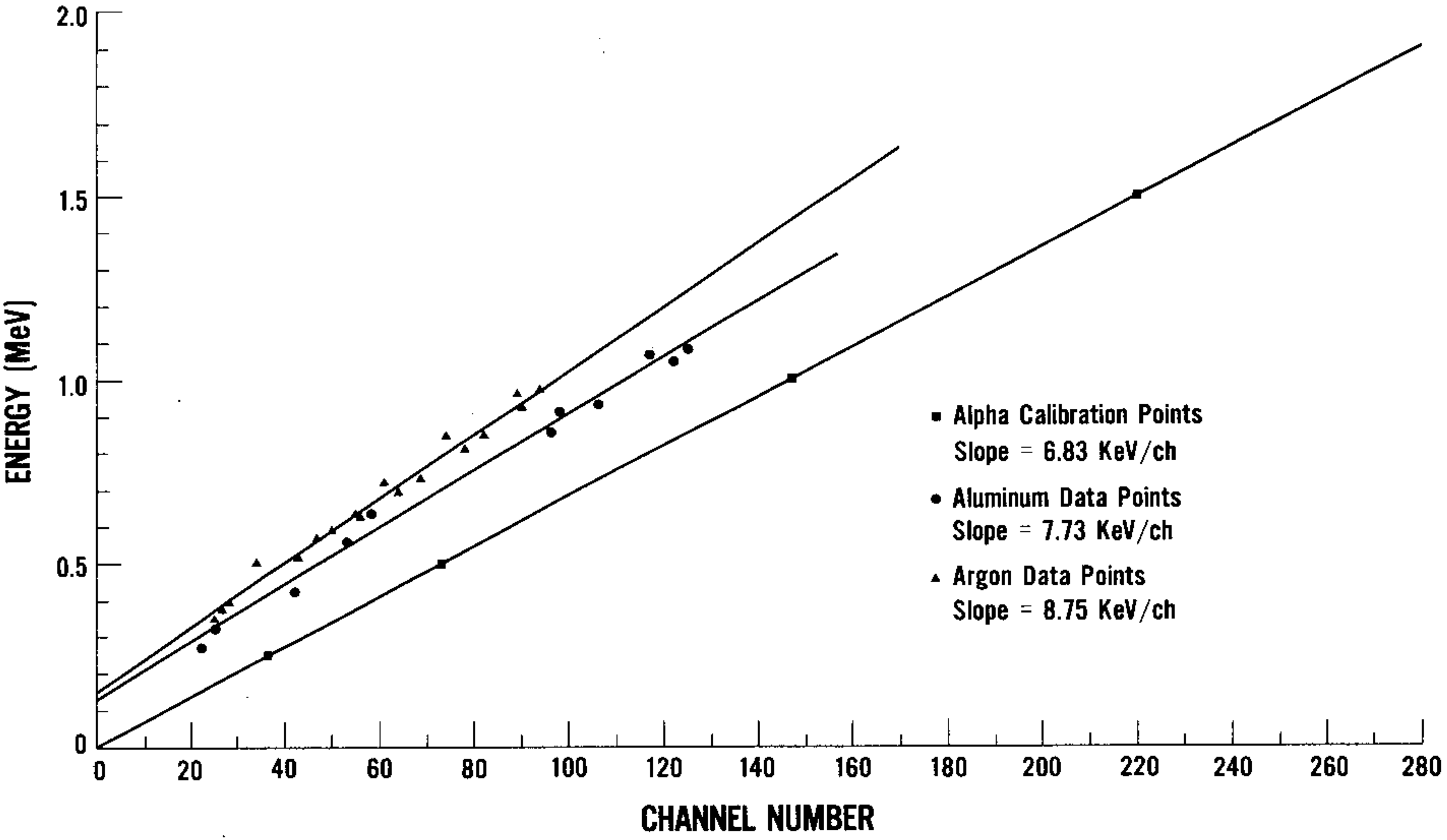
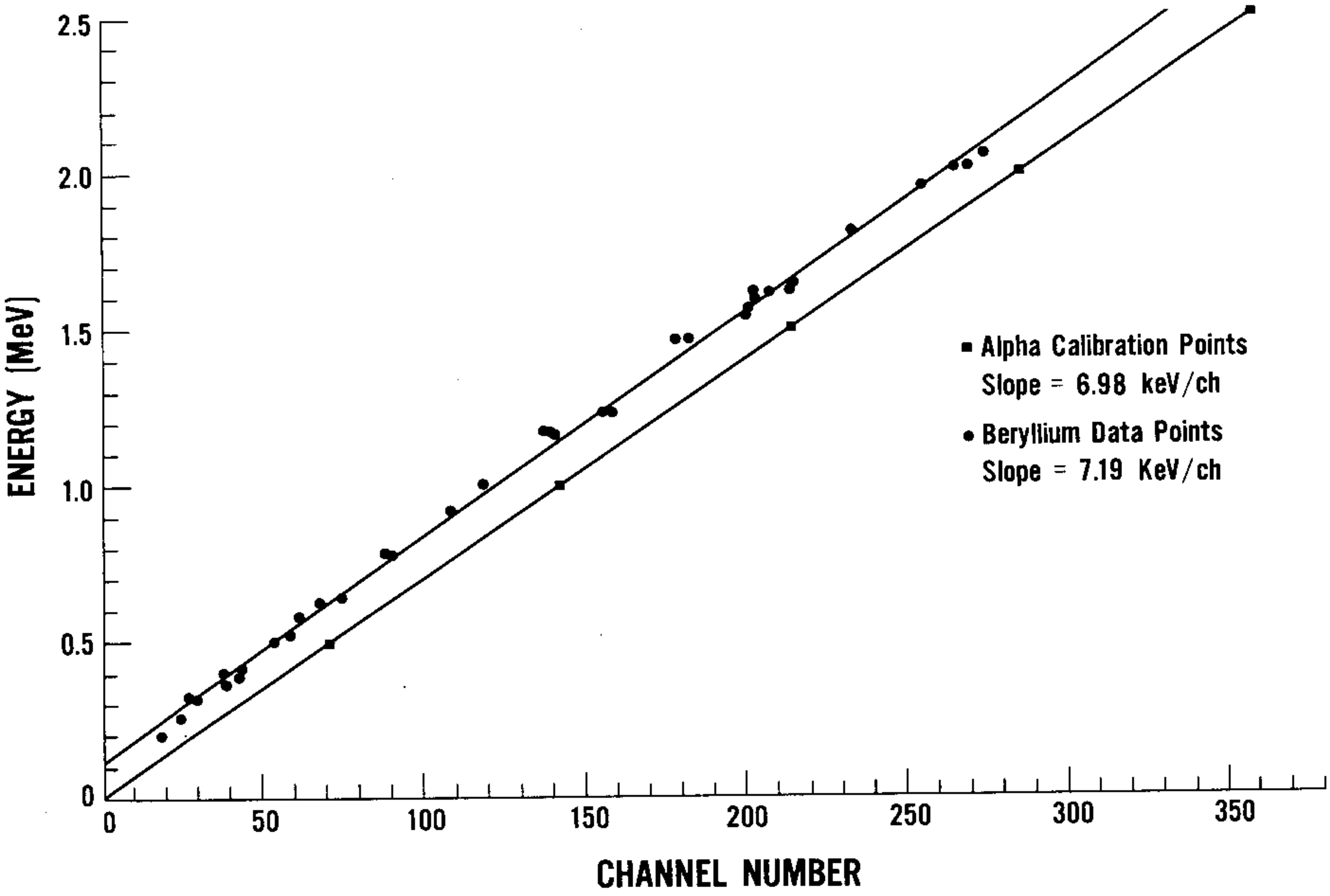

ENERGY (MeV)
2.0
1.5
1.0
0.5
0
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
CHANNEL NUMBER
■ Alpha Calibration Points
Slope = 6.83 KeV/ch
● Aluminum Data Points
Slope = 7.73 KeV/ch
▲ Argon Data Points
Slope = 8.75 KeV/ch

Figure 12. Calibration Curve for Charged Particle Detector Showing Pulse Height Defect for Be^+ Ions


2.5
2.0
1.5
1.0
0.5
0
ENERGY (MeV)
0
50
100
150
200
250
300
350
CHANNEL NUMBER
■ Alpha Calibration Points
Slope = 6.98 keV/ch
● Beryllium Data Points
Slope = 7.19 KeV/ch

150^{o} detector.

Targets and Their Preparation

The energy range for the x-rays studied in this report is from 0.6 to 4.0 keV. For the study of the L- and M-shell x-rays in this range, certain contamination problems had to be minimized. Low atomic number ($Z = 9$ to 19) elements might be contaminating the carbon backings or the target elements themselves. The K-shell x-rays of these contaminants might make the analysis of the Si(Li) detector spectra more difficult. Care must be taken to prepare the targets by a method that insures low contamination. As it turns out, the K-shell x-ray production cross section drops so dramatically with increasing atomic number (See Results, Chapter V) that the only elements which presented a significant problem were Na, Mg, Al, and Si. By using stainless steel instruments and target frames, the aluminum contamination problem was very small. Sodium and magnesium were more difficult to eliminate as they are constituent ingredients of the parting agent (soap) used to aid in the removal of the carbon foil from the slides upon which they were made. Silicon contamination was a problem that could be minimized only to a certain point because of the silicon base diffusion and roughing pump oils used in the evaporator and the beam lines. A more thorough presentation of this problem is presented in other papers.[53,54]

The carbon support foils used to back the target elements of interest were purchased from Micromatter, Inc. of Eastsound, Washington. The thickness ranged from 5 µg/cm^2 to 20 µg/cm^2. The carbon was deposited and shipped on glass slides coated with a soap used as a parting agent. In our target processing room, these foils were separated from the slides by slowly immersing them in 60° to 75° ultra-pure water obtained from Dr. Bertagnelli of the NTSU Biochemistry Department. The foils were then transferred to another container of ultra-pure water and allowed to "soak" enabling the detergent residue left on the foil to dissolve into the water. The foils were then extracted from the water by lifting them out on their target frame holders. After drying for some time, the foils were examined for any contamination by mounting them in the target chamber described earlier and examining the contaminant x-rays resulting from proton beam bombardment.

Those targets which showed little K-shell contamination were then placed in a VEECO VE-400 evaporation system with the appropriate target material placed in a tungsten evaporation boat. The whole system was then slowly evacuated to 2×10^{-7} torr. The boat was heated by an electrical current causing the evaporation of the target material. The targets were then removed from the evaporator and loaded into the beam line target chamber. These targets were scanned for the appropriate x-rays and the target thicknesses were measured using 1.5 or 2.0 MeV $^4He^+$ beam. Table III lists all the targets, their elemental thicknesses (at an angle of 45° with respect to the beam), and the compounds evaporated on the carbon backings. The total uncertainties in the target thicknesses range from 5 - 9%, due mostly to counting statistics, solid angle uncertainty, beam energy uncertainty, and the nonuniformity of the elemental target layer.

TABLE III

Target Specifications

K-shell Measurements

Element	Compound	Thickness (μg/cm^2)
$_9$F	LiF	12.6
$_{11}$Na	NaCl	2.13
$_{13}$Al	Al	7.85
$_{14}$Si	Si	10.2
$_{15}$P	Zn_3P_2	12.6
$_{17}$Cl	NaCl	3.23
$_{19}$K	KBr	19.7

L-shell Measurements

Element	Compound	Thickness (μg/cm^2)
$_{28}$Ni	Ni	4.8 *
$_{29}$Cu	Cu	11.2 *
$_{30}$Zn	Zn_3P_2	31.0
$_{32}$Ge	Ge	15.0 *
$_{33}$As	As	7.34
$_{35}$Br	KBr	36.2
$_{40}$Zr	ZrO_2	13.6
$_{46}$Pd	Pd	12.4
$_{47}$Ag	Ag	31.0

TABLE III (Con't)

Target Specifications

M-shell Measurements

Element	Compound	Thickness ($\mu g/cm^2$)
$_{59}Pr$	PrF_3	15.0 *
$_{60}Nd$	NdF_3	17.9
$_{63}Eu$	EuF_3	15.2 *
$_{64}Gd$	GdF_3	20.4
$_{66}Dy$	DyF_3	13.0 *
$_{67}Ho$	HoF_3	14.5
$_{71}Lu$	LuF_3	15.0 **
$_{72}Hf$	Hf	14.2 *
$_{74}W$	W on ZrO_2	0.5 **
$_{79}Au$	Au	14.4 *
$_{82}Pb$	Pb	5.81
$_{83}Bi$	Bi	4.35
$_{92}U$	UF_4	5.0 *

* Average thickness of targets used.

** Estimated but not measured.

CHAPTER IV

DATA REDUCTION AND ANALYSIS

Electrical signals obtained from the simultaneous measurement of the scattered particles and the x-rays emitted in this experiment were processed by the Ortec 7050 analyzer system and displayed in a histogram fashion with the number of counts per channel as a function of channel number. The resultant yields for photopeak x-rays, scattered particles, and pulse generator sums were extracted from the spectra. These yields were then used to calculate the probability for a particular ion-atom interaction resulting in the emission of a particular x-ray (x-ray production cross section). The process of spectral analysis and data reduction is outlined in this chapter.

General X-ray Production Cross Section

The experimental x-ray production cross section for the "i"th x-ray is determined by:

$$\sigma_{xi} = \frac{d\sigma_{xi}}{d\Omega} = \frac{Y_{xi}\ t_x}{N_0 N_1 \varepsilon_i} \qquad \text{(IV-1)}$$

where:

Y_{xi} is the total yield under the i^{th} x-ray photopeak,

t_x is the dead time correction to the detector yield,

ε_i is the efficiency of the Si(Li) detector for the i^{th}

x-ray (including the solid angle subtended),

N_o is the thickness of the target in atoms/cm^2, and

N_1 is the total number of particles incident upon the target.

This calculation gives the x-ray production cross section in cm^2 per incident particle for a particular (ith) x-ray. Measuring the target thickness and determining the total number of incident particles is difficult for heavy ions and introduces large uncertainties. The problems encountered, due to the accurate determination of N_0 and N_1, can be circumvented by simultaneously measuring the differential Rutherford scattering cross section. This is given by:

$$\frac{d\sigma_R}{d\Omega} = \frac{Y_R\ t_R}{N_o N_1 \Delta\Omega} \tag{IV-2}$$

where:

Y_R is the total yield in the particle detector for the scattering of the heavy ion from the target element of interest,

t_R is the dead time correction to the detector yield,

$\Delta\Omega$ is the solid angle of the particle detector,

N_o is the thickness of the target in atoms/cm^2, and

N_1 is the total number of particles incident upon the target.

These two equations can be solved for N_o and N_1 and combined to give:

$$\sigma_{xi} = \left[\frac{Y_{xi}\ t_x}{Y_R\ t_R}\right]\left[\frac{\Delta\Omega}{\varepsilon_{xi}}\right]\left(\frac{d\sigma_R}{d\Omega}\right) \tag{IV-3}$$

This simultaneous measurement eliminates the problem resulting from accurate determination of the heavy ion's exit charge state and the variations in the target thickness layers. The yields are computed from the spectra, the solid angle was measured by a calibrated alpha source (See Chapter III), and the efficiency was determined by a normalization process described in Chapter III. Only the differential Rutherford cross section remains as an unknown, but it can be calculated by using the theoretical approximation:

$$\frac{d\sigma_R}{d\Omega} \doteq (1.296 \times 10^{-3}\ \text{barns/sr})\left[\frac{Z_1 Z_2}{E_1}\right]\left[\sin^{-4}(\theta/2) - 2\left(\frac{M_1}{M_2}\right)^2\right] \tag{IV-4}$$

where:

Z_1 is the atomic number of the incident ion,

Z_2 is the atomic number of the target atom,

M_1 is the atomic mass number of the incident ion,

M_2 is the atomic mass number of the target atom,

E_1 is the incident laboratory projectile energy, and

θ is the laboratory scattering angle measured with respect to the forward beam direction.

When using this technique of simultaneous measurement, one assumes that only Rutherford scattering takes place resulting in the Rutherford particle yield (Y_R) being proportional to the number of incident particles (N_1). This assumption is true only if the ion beam incident energy is significantly below the Coulomb barrier for nuclear reactions. The smallest Coulomb barrier encountered in this work was 26 MeV for $^{9}_{4}Be^{+}$ ions incident upon fluorine atoms. This is more than ten times the maximum energy studied here. Thus, the assumption that the nuclear-nuclear interactions are purely Rutherford in nature is good for all the data reported in this dissertation.

Energy Loss Correction Factor

As the projectile enters the target, it loses energy by interactions with the target atoms and electrons. Therefore, there is a difference in the projectile's energy at the front surface and at the back surface of the target. The x-ray production cross section has been found to depend heavily on the projectile energy.[76] This dependence can be expressed as $Y_x \propto (E_1)^s$, where s is the slope of the plot of the x-ray production cross section versus incident projectile energy. Therefore, as the projectile energy decreases the yield will also decrease by:[76]

$$\frac{dY_x}{Y_x} = S\,\frac{dE_1}{E_1} \qquad \text{(IV-5)}$$

The Rutherford scattering cross section is also energy dependent (See equation IV-4) and this, too, must be considered. The energy dependence of the particle yield is $Y_R \propto (E_1)^{-2}$. This yield, therefore, increases with decreasing projectile energy as

$$\frac{dY_R}{Y_R} = -2\frac{dE_1}{E_1} \qquad \text{(IV-6)}$$

The total energy loss (E.L.) correction factor due to non-zero target thickness has been evaluated[76] to be

$$\text{E.L. Factor} = \left[1 - \frac{\overline{\Delta E}}{E_1}\right]^{-(S+2)} \qquad \text{(IV-7)}$$

where $\overline{\Delta E}$ is the average energy lost by the projectile as it passes through the target material. It is given by

$$\overline{\Delta E} = \left(\frac{dE}{dX}\right)\frac{\rho t}{2} \qquad \text{(IV-8)}$$

where dE/dx is the stopping power for the incident ion in the target material at the incident energy, and ρt is the target thickness. For the work presented here, the targets are thin enough to insure that this correction factor remains small for all beryllium results. For example, with Be incident upon an aluminum target (7.85 μg/cm^2) the correction factors range from 1.03 for 2.5 MeV to 1.08 for 0.5 MeV. The total change is less than an 8% increase in the cross section. Since higher Z targets have a lower stopping power, the corrections to their cross sections would be even less.

Correction Factor for Target Absorption of X-rays

The x-rays generated in the target must penetrate some target material and the carbon foil backing in order to reach the Si(Li) x-ray detector (See figures 5 and 6). With non-zero thicknesses, these layers will attenuate the x-ray intensity. A procedure to account for this loss was developed by Basbas, Brandt, and Laubert[21] and is also presented in the dissertation by Mehta.[77] For self-absorption (S.A.) in the target material, the resulting correction factor is written as:

$$\text{S.A. Factor} = \left[\frac{1 - \exp(-\mu_i \varrho t)}{\mu_i \varrho t} \right] \qquad \text{(IV-9)}$$

where μ_i is the absorption coefficient for the i^{th} x-ray in the target material, and ϱt is the thickness of the layer. The total correction remains less than 1.3% for the absorption in the target material for the K-, L-, and M-shell data. The absorption in the carbon remains less than 1% for all targets except for the fluorine K-shell data where the correction is as large as 3%.

With all the appropriate correction terms, the final equation for data analysis becomes

$$\sigma_{xi} = \left(1.296 \times 10^{-3}\ \mathrm{bn/sr}\right) \left[\frac{Y_{xi}\ t_x}{Y_R\ t_R}\right] \left[\frac{\Delta\Omega}{\varepsilon_{xi}}\right] \left[\frac{Z_1 Z_2}{E_1}\right] \left[1 - \frac{\overline{\Delta E}}{E_1}\right]^{-(s+2)}$$

$$\times \left[\sin^{-4}(\theta/2) - 2\left(\frac{M_1}{M_2}\right)^2\right] \left[\frac{1 - \exp(-\mu_i \rho t)}{\mu_i \rho t}\right] \qquad \text{(IV-10)}$$

Total X-ray Production Cross Sections

The x-rays being studied are very low in energy and thus have a small separation between the subshell energies. For the $_9F$ to $_{15}P$ targets, the energy difference between the K-subshells ($\Delta E_K = E_{K\alpha} - E_{K\beta}$) is less than the detector x-ray resolution. Multiple ionizations in the targets, in addition to its other effects, will broaden the K-shell x-ray peaks and thus the resolution of the K_α and K_β peaks for $_{17}Cl$, $_{19}K$, and $_{20}Ca$ is impossible. In addition to the difficulty in determining the yields of the individual K-subshell lines, their associated efficiencies were also indeterminate. Choosing as the total efficiency that which is associated with the dominant x-ray line (K_α), we have the best approximation for the actual detector efficiency. Therefore, the results listed are for total K-shell x-ray production cross sections. Using $\varepsilon_{K\alpha}$ as the efficiency for the K_β x-ray, equation IV-3 becomes:

$$\sigma_{XK} = \sigma_{XK\alpha} + \sigma_{XK\beta} = \left(\frac{Y_{XK\alpha}}{\varepsilon_{K\alpha}} + \frac{Y_{XK\beta}}{\varepsilon_{K\beta}} \right) \frac{\Delta\Omega}{Y_R} \frac{t_x}{t_R} \left(\frac{d\sigma_R}{d\Omega} \right)$$

$$\doteq \frac{\left(Y_{XK\alpha} + Y_{XK\beta} \right) \Delta\Omega \; t_x}{Y_R \qquad \epsilon_{K\alpha} \; t_R} \left(\frac{d\sigma_R}{d\Omega} \right) \qquad \text{(IV-11)}$$

Similarly, for the L-shell targets, these same problems arose. For $_{28}$Ni to $_{40}$Zr targets, resolution of the L_α, L_β, and the L_γ x-rays is impossible. Again, the efficiency of the dominant peak (L_α) was chosen to be the efficiency of the broad x-ray peak. Using $\sum_{i=1}^{3} Y_{XLi} = Y_{XL}$, equation IV-3 becomes:

$$\sigma_{XL} = \sum_{i=1}^{3} \sigma_{XLi} \doteq \frac{Y_{XL} \; t_x \; \Delta\Omega}{Y_R \; t_R \; \varepsilon_{L\alpha}} \left(\frac{d\sigma_R}{d\Omega} \right) \qquad \text{(IV-12)}$$

Again, the same problems exist for the M-shell targets. The efficiency is chosen to be the efficiency for the dominant x-ray line (M_α). Using $\sum_{i=1}^{5} Y_{XMi} = Y_{XM}$, equation IV-3 becomes:

$$\sigma_{XM} = \sum_{i=1}^{5} \sigma_{XMi} \doteq \frac{Y_{XM} \; t_x \; \Delta\Omega}{Y_R \; t_R \; \varepsilon_{M\alpha}} \left(\frac{d\sigma_R}{d\Omega} \right) \qquad \text{(IV-13)}$$

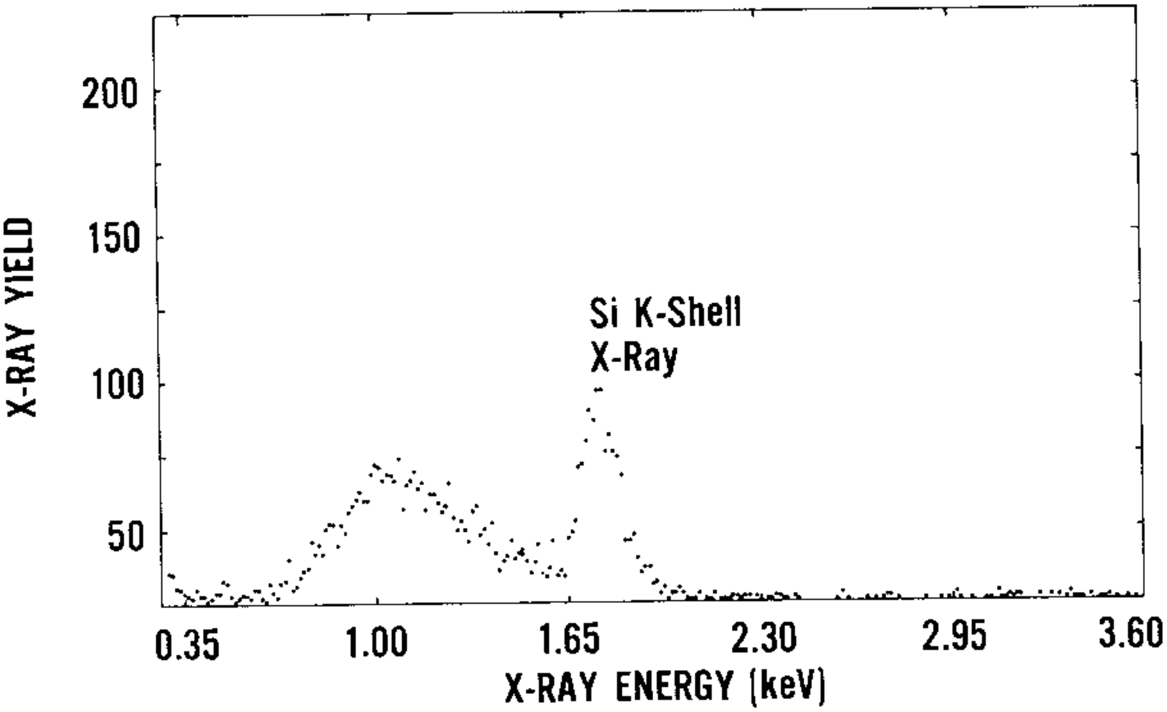
Spectrum Analysis

To analyze a spectrum, it was necessary to estimate the background and subtract it from the total spectrum. This is true for both particle and x-ray spectra. The background was estimated and then fit by a least squares method with a second order polynomial. This process of background fitting and subtraction becomes very important for low ion beam energy particle spectra and high ion beam energy x-ray spectra.

Low ion beam energy particle spectra show a smaller peak separation for the elements present in the target and might necessitate peak fitting or background subtraction. Figure 7 shows particle spectra for 1.0 and 2.5 MeV Be^+ ions incident upon a KBr target. Notice that the dominant peaks (particles scattered from carbon, potassium, and bromine atoms in the target) have larger peak separations for the higher energy spectrum.

High ion beam energy x-ray spectra show higher background levels which had to be subtracted. Most of this background came from contaminants present in the target material and the carbon foil backing. For the Al^+ and Ar^+ data, there were aluminum and argon K-shell x-ray peaks present which also had to be subtracted as background in some cases. Figures 13, 14, and 15 show low and high energy beryllium ion beam induced x-ray spectra for silicon (K-shell), copper (L-shell), and gold (M-shell) cross section analysis. Notice the increase in the background for the higher beam

Figure 13. K-shell X-ray Spectra for 1.0 (top) and 2.5 MeV (bottom) Be^+ Ions on Silicon


X-RAY YIELD
200
150
100
50
Si K-Shell
X-Ray
0.35
1.00
1.65
2.30
2.95
3.60
X-RAY ENERGY (keV)

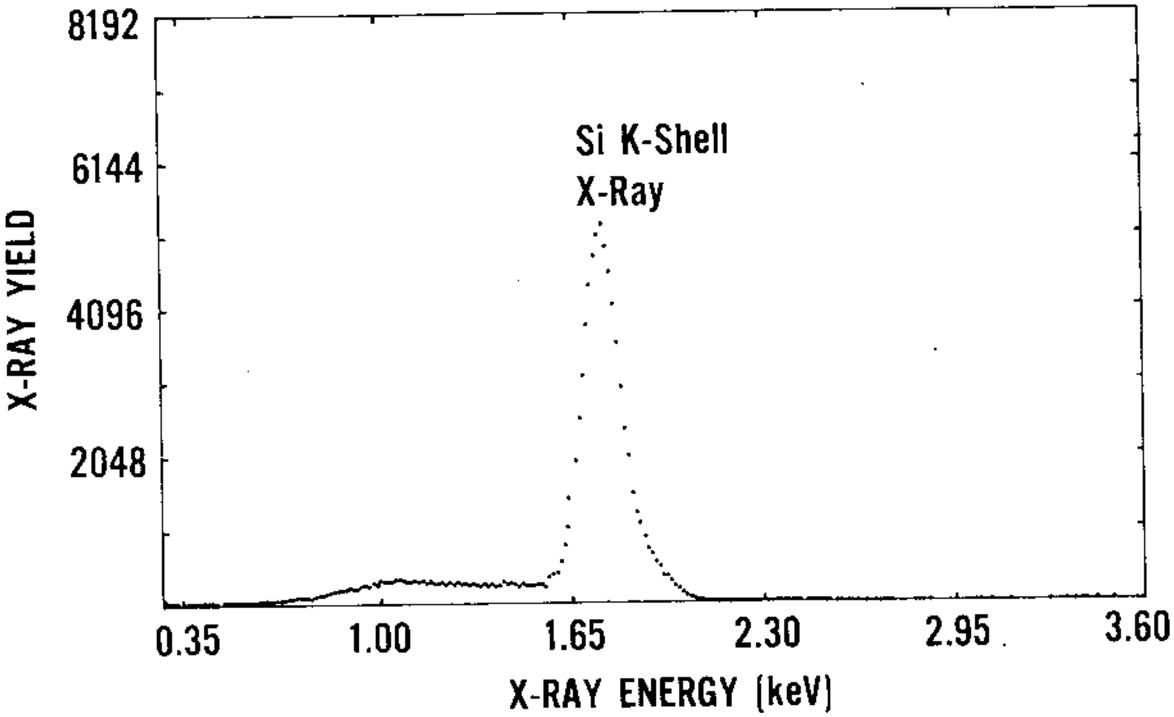
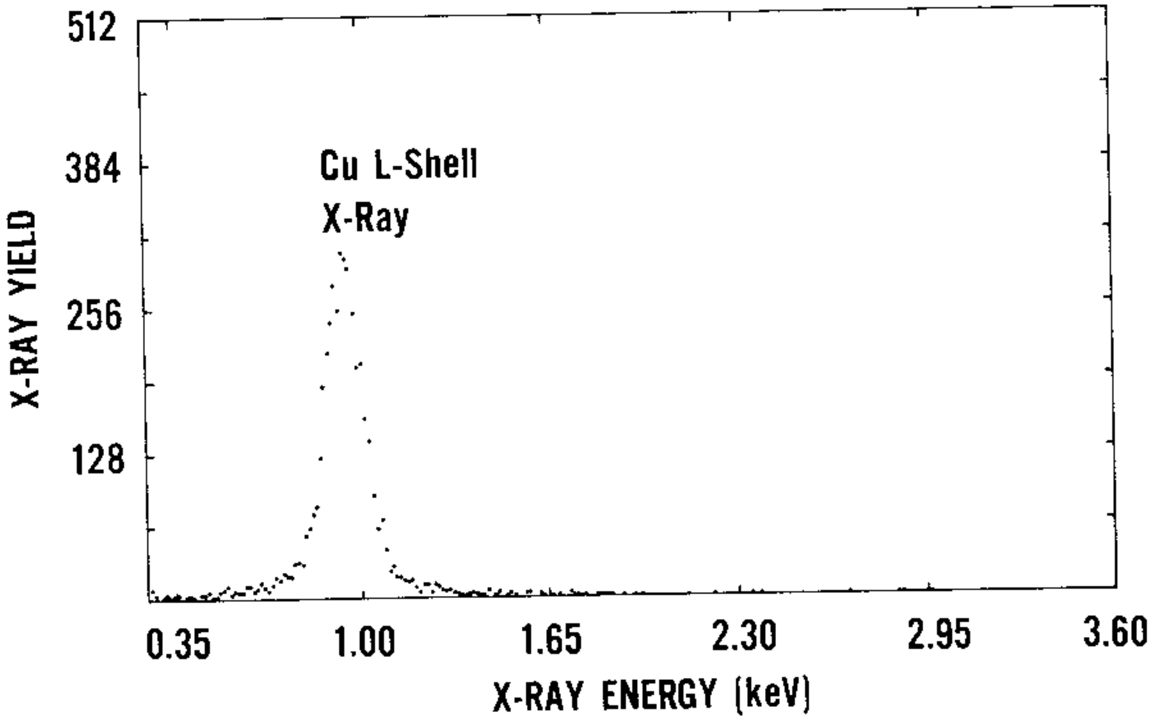

X-RAY YIELD
8192
6144
4096
2048
Si K-Shell
X-Ray
0.35
1.00
1.65
2.30
2.95
3.60
X-RAY ENERGY (keV)

Figure 14. L-shell X-ray Spectra for 1.0 (top) and 2.5 MeV (bottom) Be^+ Ions on Copper


512
384
256
128
X-RAY YIELD
Cu L-Shell
X-Ray
0.35
1.00
1.65
2.30
2.95
3.60
X-RAY ENERGY (keV)

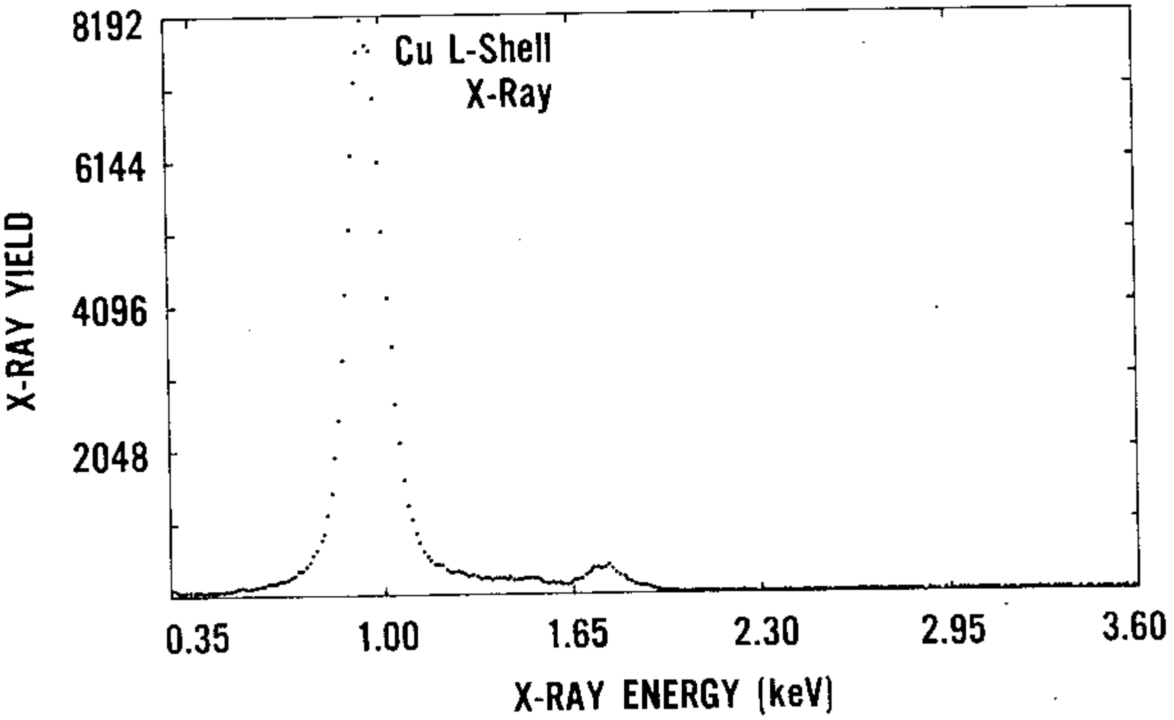
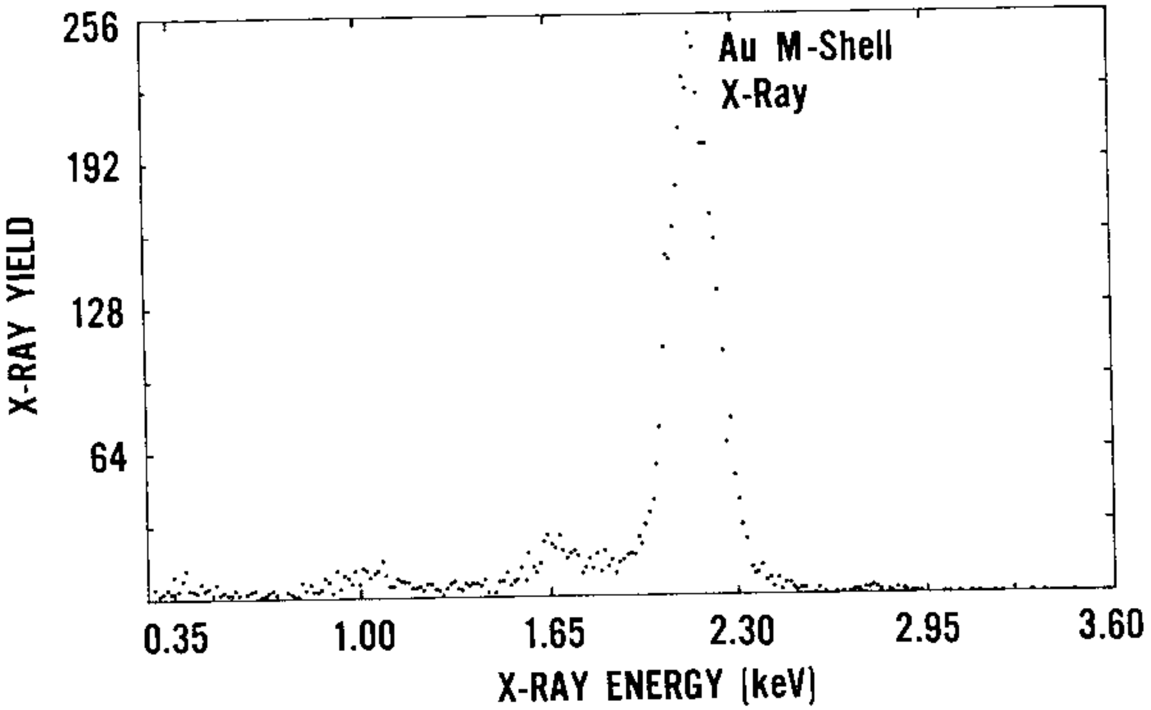
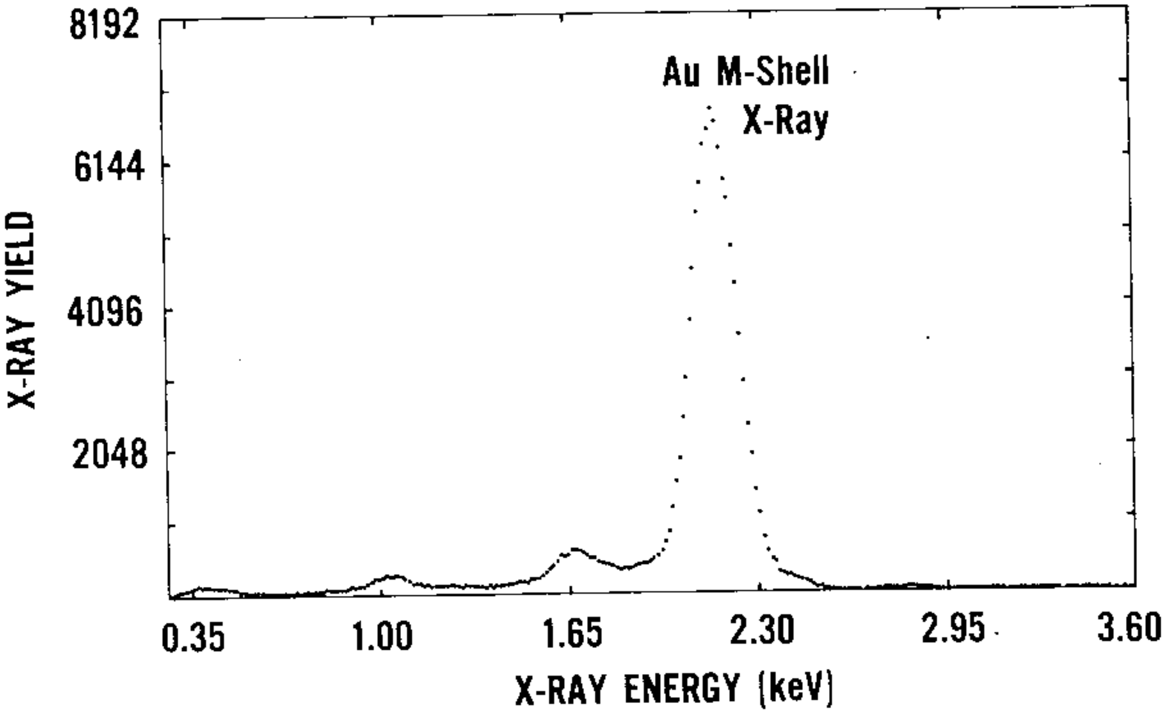

8192
6144
4096
2048
X-RAY YIELD
Cu L-Shell
X-Ray
0.35
1.00
1.65
2.30
2.95
3.60
X-RAY ENERGY (keV)

Figure 15. M-shell X-ray Spectra for 1.0 (top) and 2.5 MeV (bottom) Be^+ Ions on Gold


Au M-Shell
X-Ray
256
192
128
64
X-RAY YIELD
0.35
1.00
1.65
2.30
2.95
3.60
X-RAY ENERGY (keV)


Au M-Shell
X-Ray
8192
6144
4096
2048
X-RAY YIELD
0.35
1.00
1.65
2.30
2.95
3.60
X-RAY ENERGY (keV)

energy spectra which necessitates some kind of spectral subtraction. Figure 16 shows the x-ray spectrum for an Al^+ ion beam incident upon a dysprosium target. The dominance of the Al K-shell x-ray is apparent and requires some peak fitting method to extract reliable yields for the Dy x-ray peak.

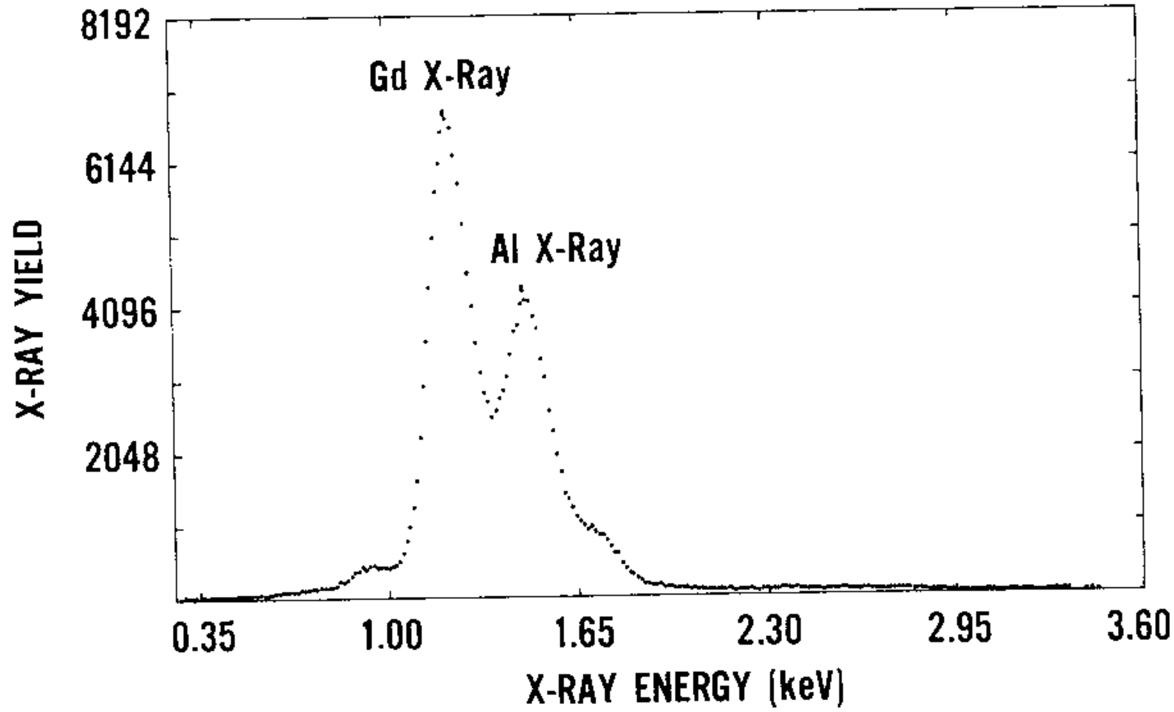
Error Analysis

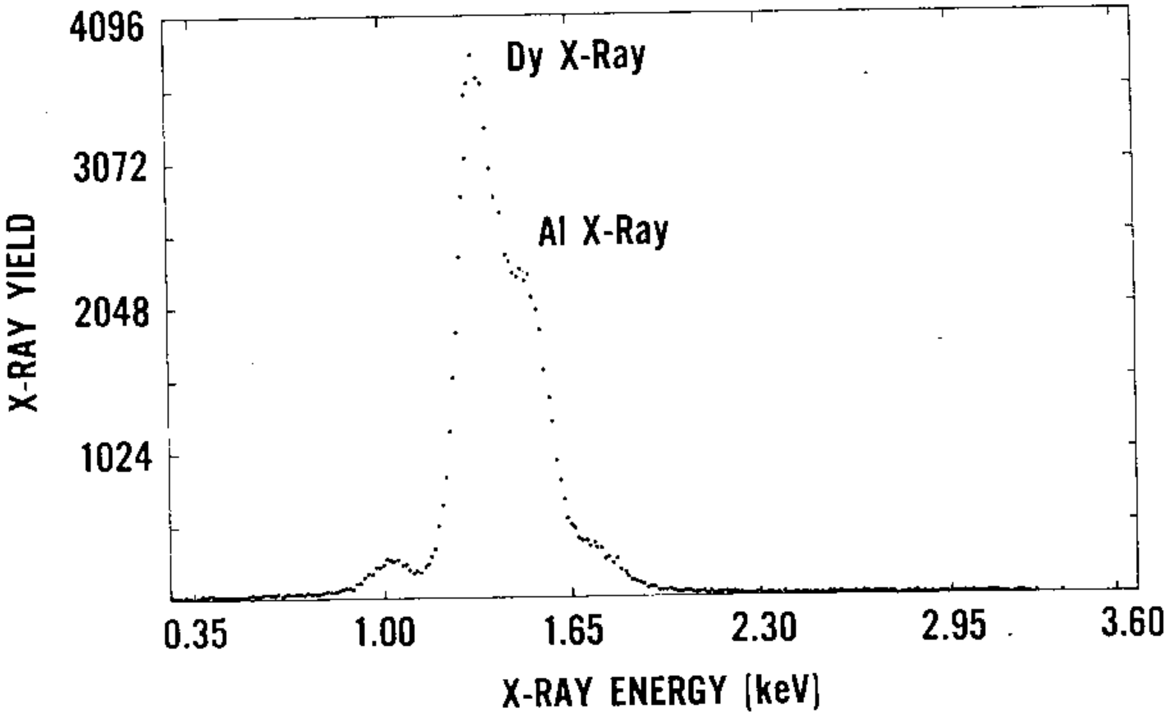
The experimental uncertainties may divided into two types, the relative experimental uncertainties between like data and the uncertainties involved in normalization of the data to absolute scales. The relative uncertainties are comprised of (i) uncertainties in counting statistics and background subtraction for x-ray and particle yields, also (ii) incident energy uncertainties due to mass-energy calibration of the bending magnet. The total relative uncertainties were calculated by standard methods derived from Beers.[78] The standard deviation (S) in the net yield from the spectrum is given by

$$S_{Net} = \sqrt{G^2 + B^2}$$

where G is the gross (total) number of counts in the peak and B is the background count subtracted from the peak. This resulted in the percent uncertainty in the yields as ($Y^{-1}\ S_{net}$), where Y is the net yield. This percentage was then added in quadrature to the other percentage

Figure 16. M-shell X-ray Spectra for 1.5 MeV Al^+ Ions on Gadolinium and Dysprosium


8192
6144
4096
2048
X-RAY YIELD
Gd X-Ray
Al X-Ray
0.35
1.00
1.65
2.30
2.95
3.60
X-RAY ENERGY (keV)


4096
3072
2048
1024
X-RAY YIELD
Dy X-Ray
Al X-Ray
0.35
1.00
1.65
2.30
2.95
3.60
X-RAY ENERGY (keV)

uncertainties to give the total relative uncertainty.

The normalization uncertainties are comprised primarily of (i) efficiency uncertainties, (ii) uncertainty in the particle detector solid angle, and (iii) uncertainty in the particle detector angle. These percentage uncertainties were added in quadrature. The ranges of the experimental uncertainties involved with the measurements presented here are listed in Table IV.

TABLE IV

EXPERIMENTAL UNCERTAINTIES

Source	Range Be^+ ion data	 Al^+ ion data	 Ar^+ ion data
I. Relative Uncertainties			
A. Counting Statistics			
1. X-ray yields	1% - 15%	1% - 25%	1% - 25%
2. Particle yields	1% - 15%	1% - 20%	1% - 15%
3. Background fitting	5% - 10%	10% - 25%	10% - 20%
B. Beam Energy Determination	4% - 20%	4% - 20%	4% - 20%
Total Relative Uncertainty	15% - 28%	22% - 42%	19% - 38%
II. Normalization Uncertainties			
A. Efficiencies	7% - 40%	7% - 40%	7% - 40%
B. Particle Detector Solid Angle	2.3%	2.3%	2.3%
C. Particle Detector Position	5%	5%	5%
Total Normalization Uncertainty	8.9% - 41%	8.9% - 41%	8.9% - 41%
III. Total Absolute Uncertainty	16% - 42%	23% - 59%	20% - 55%

CHAPTER V

RESULTS AND DISCUSSION

The results of this study are presented in four sections: (i) $^{9}Be^{+}$ ion measurements, (ii) $^{27}Al^{+}$ ion measurements, (iii) $^{40}Ar^{+}$ ion measurements, and (iv) analysis and conclusion. In the first three sections of this chapter, the x-ray production cross section results are presented in tabular form (measured cross sections and ECPSSR predictions), plotted as a function of incident ion energy, and plotted as a function of target atomic numbers. The specific results of the calculations for both the First Born and ECPSSR theories are presented in Appendices A through F. In these appendices, x-ray production cross sections are listed under the column headings "XRAY PROD" or "X-RAY PRODUCTION." The total ionization cross sections are listed under the column headings "IONIZATION" or "DI + EC." The specific portion of the total ionization cross section due to direct ionization and electron capture are listed under the appropriate columns. The "C/I" column lists the ratios of the electron capture contribution to the total ionization. All measurements were taken at NTSU as described in Chapter III and evaluated as described in Chapter IV.

$^{9}Be^{+}$ Data

The measurements of the x-ray production cross sections by incident $^{9}Be^{+}$ ions are presented here. The results are divided into three groups: (i) K-shell, (ii) L-shell, and (iii) M-shell measurements.

K-shell Results

The measured total K-shell x-ray production cross sections for $^{9}_{4}Be^{+}$ ions incident upon $_{9}F$, $_{11}Na$, $_{13}Al$, $_{14}Si$, $_{15}P$, $_{17}Cl$, and $_{19}K$ are presented as a function of incident ion energy in Figures 17 and 18. The predictions of the First Born (broken line) and ECPSSR (solid line) theories are also presented in these figures. Table V lists the actual measured values and the associated predictions of the ECPSSR theory. Appendix A gives more detailed results of the theoretical prediction for both the First Born and ECPSSR formalisms.

From Figures 17 and 18 certain trends can be observed: (i) the First Born theory greatly overpredicts the measured values, sometimes by as much as a factor of 25, while (ii) the ECPSSR theory has very good general agreement. There is a slight underprediction at low energies and overprediction at high energies for the ECPSSR. Figure 19 displays the ECPSSR theory predictions and measured results as a function of target atomic number. The general trend indicated is that for heavier targets (higher atomic number)

TABLE V

K-SHELL X-RAY PRODUCTION CROSS SECTIONS (BARNS) FOR INCIDENT ${}^{9}_{4}Be^{+}$ Ions

Target		BEAM ENERGY (MeV)								
		0.50	0.75	1.00	1.25	1.50	1.75	2.00	2.25	2.50
$_{9}F$	Measured	- - -	- - -	127	297	688	1570	3470	4100	- - -
	ECPSSR	4.13	39.2	185	570	1320	2500	4110	6070	8340
$_{11}Na$	Measured	6.32	11.0	24.6	58.7	135	240	319	535	884
	ECPSSR	0.614	4.97	21.7	66.8	162	331	597	970	1460
$_{13}Al$	Measured	0.440	1.34	3.64	10.9	26.7	32.7	68.6	98.1	189
	ECPSSR	0.145	1.10	4.48	13.2	31.3	64.4	118	199	312
$_{14}Si$	Measured	0.195	0.774	1.98	5.48	8.07	18.3	35.7	51.3	84.6
	ECPSSR	0.0785	0.592	2.37	6.84	16.1	32.8	60.1	101	160
$_{15}P$	Measured	0.0834	0.325	0.691	2.33	4.83	9.50	15.3	23.4	40.9
	ECPSSR	0.0439	0.335	1.32	3.77	8.75	17.7	32.3	54.4	86.0
$_{17}Cl$	Measured	0.0570	0.176	0.507	1.24	3.00	5.54	10.5	13.4	27.3
	ECPSSR	0.0153	0.124	0.491	1.38	3.16	6.30	11.4	19.1	30.1
$_{19}K$	Measured	0.00507	0.0522	0.227	0.615	1.10	2.27	3.40	5.32	- - -
	ECPSSR	0.00540	0.0485	0.197	0.556	1.27	2.52	4.52	7.52	11.8

Figure 17. Energy Dependence of the K-shell X-ray Production Cross Section for Be^+ Ions Incident upon Fluorine, Aluminum, Phosphorus and Potassium Targets

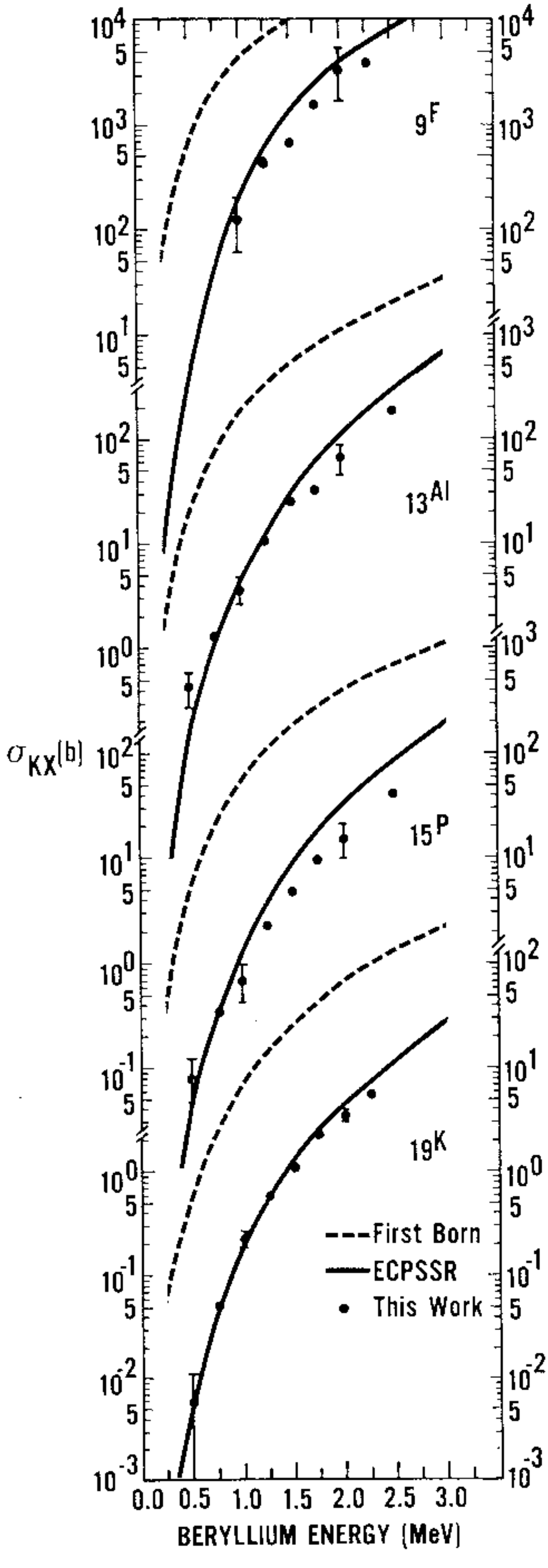
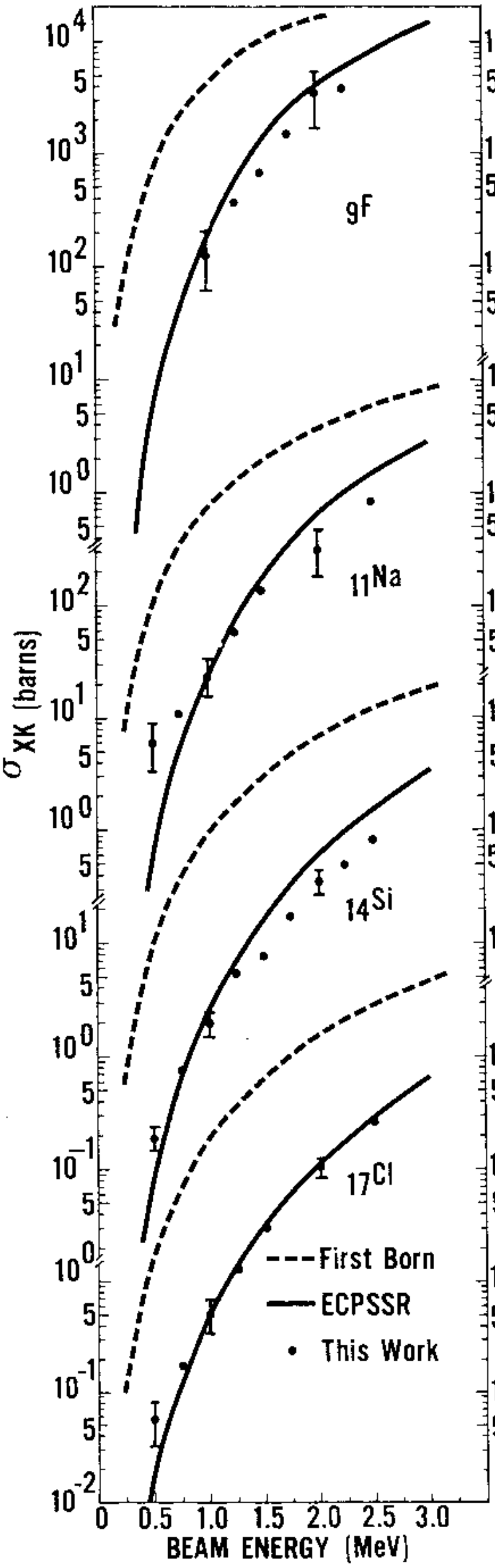
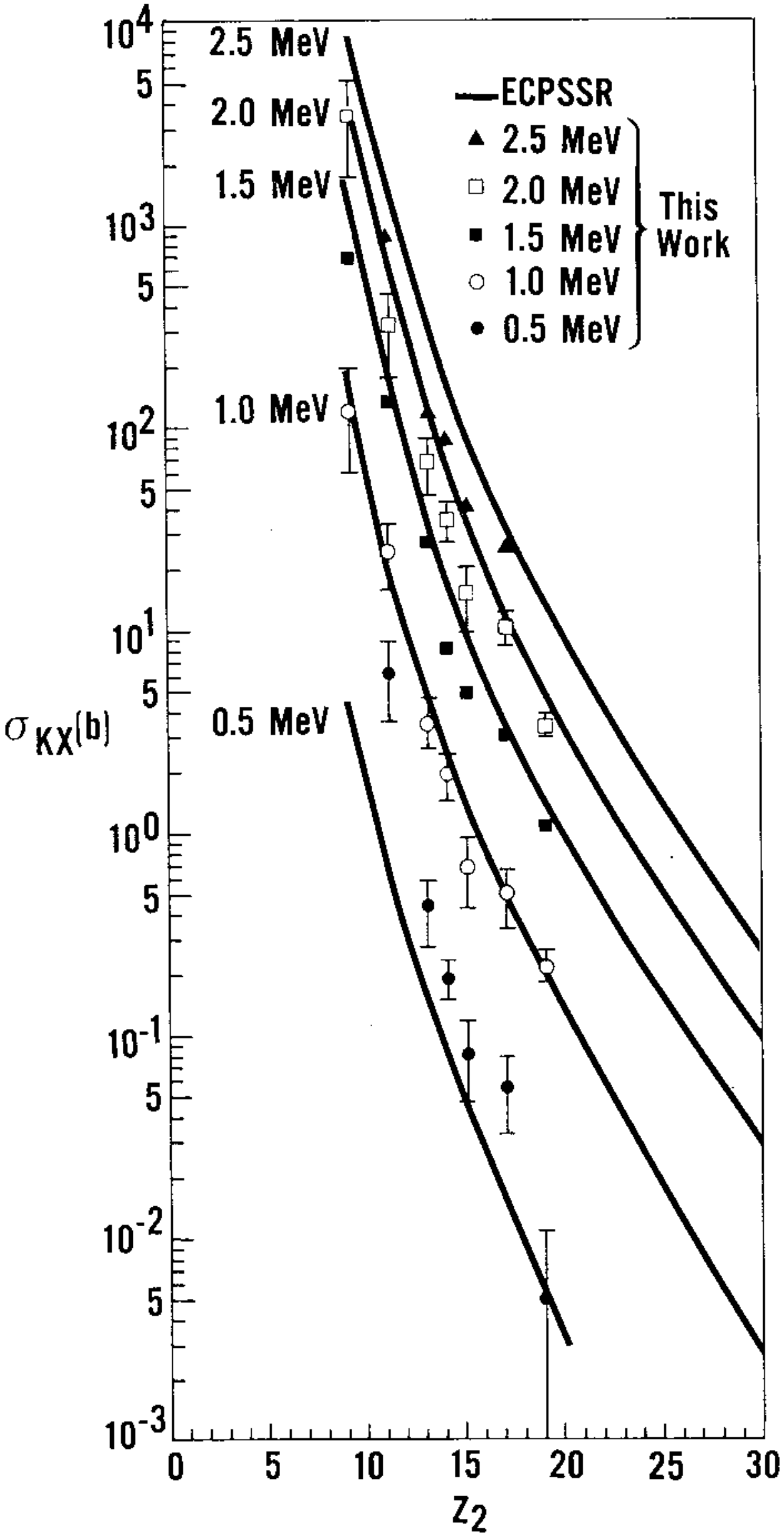

σ_{KX}(b)
9^F
13^{Al}
15^P
19^K
10^4
5
10^3
5
10^2
5
10^1
5
10^0
5
10^{-1}
5
10^{-2}
5
10^{-3}
---First Born
ECPSSR
• This Work
0.0 0.5 1.0 1.5 2.0 2.5 3.0
BERYLLIUM ENERGY (MeV)

Figure 18. Energy Dependence of the K-shell X-ray Production Cross Section for Be^+ Ions Incident upon Fluorine, Sodium, Silicon, and Chlorine Targets



σ_{XK} (barns)
BEAM ENERGY (MeV)
0
0.5
1.0
1.5
2.0
2.5
3.0
$_9$F
$_{11}$Na
$_{14}$Si
$_{17}$Cl
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
5
First Born
ECPSSR
This Work

Figure 19. Target Atomic Number Dependence of the K-shell X-ray Production Cross Section for Be^+ Ions



2.5 MeV
2.0 MeV
1.5 MeV
1.0 MeV
0.5 MeV
ECPSSR
▲ 2.5 MeV
□ 2.0 MeV
■ 1.5 MeV
○ 1.0 MeV
● 0.5 MeV
This Work
σ_{KX}(b)
10^4
5
10^3
5
10^2
5
10^1
5
10^0
5
10^{-1}
5
10^{-2}
5
10^{-3}
0
5
10
15
20
25
30
Z_2

there is better general agreement between the ECPSSR values and the measured results at all energies. This better agreement can be attributed to the entrance into the Z_1 Z_2 region of validity for the theory.

Since the total ionization cross sections were converted to x-ray production cross sections using the single-hole fluorescence yields of Krause,[55] there are multiple ionization effects that were not taken into account. There are basically two effects: (i) the increase in binding energy causing an upward shift in x-ray energy resulting in higher Si(Li) detector efficiency in general and (ii) an increase in the fluorescence yields due to fewer electrons available for the non-radiative processes. These effects (if corrected for) would shift the theory predictions higher and result in better agreement at low beam energies. The resultant high energy discrepancy would be increased and its cause is still uncertain. At such low incident projectile velocities, the Coulomb deflection correction to the theories (which is substantial) may not accurately reflect the phenomenon (see Chapter III) and thus alter the results accordingly. Any changes in this factor would affect the low energy results more than those at higher energies.

L-shell Results

The measured total L-shell x-ray production cross sections for ${}^{9}_{4}Be^{+}$ incident upon ${}_{29}Cu$, ${}_{30}Zn$, ${}_{32}Ge$, ${}_{35}Br$, and ${}_{40}Zr$ are presented as a function of incident ion energies in Figures 20 and 21. Also presented in these figures are the predictions of the First Born (broken line) and the ECPSSR (solid line) theories. Again, the First Born predictions significantly overestimate the actual measured values by a large factor, while the ECPSSR predictions underestimate but follow the general trend very well with better agreement at higher energies. The high energy agreement could be attributed to the nearness to the region of validity of higher velocity for the ECPSSR theory.

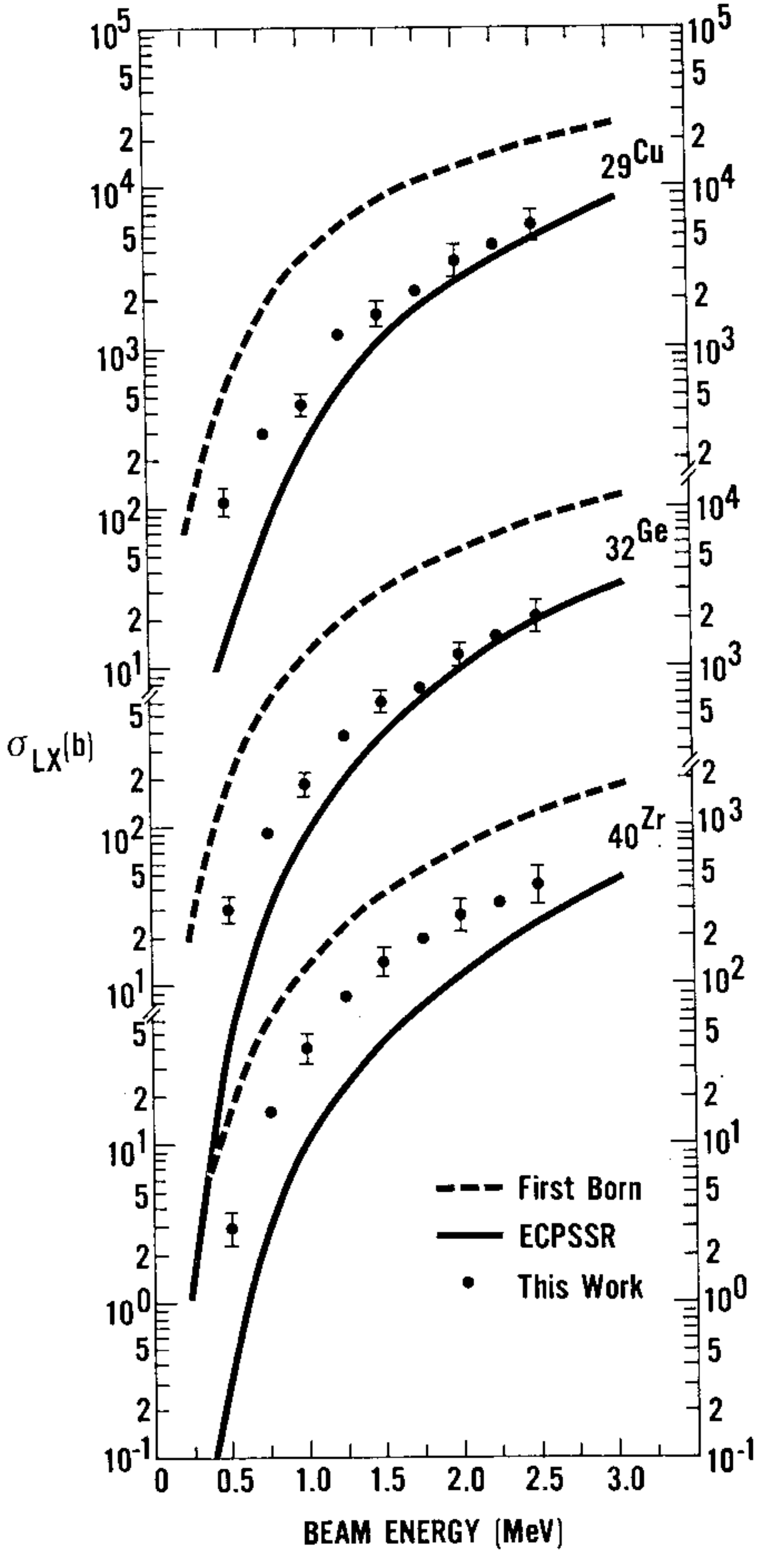
Table VI presents the numerical predictions of the ECPSSR theory and the actual measured numbers. Figure 22 presents the measured results and the ECPSSR predictions as a function of target atomic number. Again, for low energies the predictions fall significantly below the measured values, while higher energy results agree very well with theory. There does not appear to be a significant Z_2 dependence other than a slightly more enhanced underprediction at higher Z_2 than lower Z_2. This apparent effect, though, could be altered somewhat if corrections for multiple ionizations and changes in the Coulomb deflection factors are included. The correction for multiple ionization effects would raise the ECPSSR predictions

TABLE VI

L-SHELL X-RAY PRODUCTION CROSS SECTIONS (BARNS) FOR INCIDENT ${}^{9}_{4}Be^{+}$ IONS

Target		BEAM ENERGY (MeV)								
		0.5	0.75	1.0	1.25	1.5	1.75	2.0	2.25	2.5
$_{29}Cu$	Measured	1.09×10^{2}	3.08×10^{2}	4.42×10^{2}	1.26×10^{3}	1.54×10^{3}	2.31×10^{3}	3.49×10^{3}	4.28×10^{3}	5.67×10^{3}
	ECPSSR	1.44×10^{1}	8.11×10^{1}	2.50×10^{2}	5.66×10^{2}	1.06×10^{3}	1.75×10^{3}	2.65×10^{3}	3.74×10^{3}	5.00×10^{3}
$_{30}Zn$	Measured	3.43×10^{1}	1.28×10^{2}	2.40×10^{2}	5.13×10^{2}	1.02×10^{3}	1.65×10^{3}	2.12×10^{3}	2.43×10^{3}	3.56×10^{3}
	ECPSSR	9.95×10^{0}	5.62×10^{1}	1.74×10^{2}	3.94×10^{2}	7.42×10^{2}	1.23×10^{3}	1.87×10^{3}	2.66×10^{3}	3.60×10^{3}
$_{32}Ge$	Measured	2.96×10^{1}	9.58×10^{1}	1.77×10^{2}	3.71×10^{2}	6.03×10^{2}	7.50×10^{2}	1.21×10^{3}	1.52×10^{3}	2.09×10^{3}
	ECPSSR	4.97×10^{0}	2.89×10^{1}	8.99×10^{1}	2.05×10^{2}	3.89×10^{2}	6.51×10^{2}	9.99×10^{2}	1.44×10^{3}	1.96×10^{3}
$_{35}Br$	Measured	7.16×10^{0}	3.39×10^{1}	9.14×10^{1}	1.79×10^{2}	2.82×10^{2}	4.24×10^{2}	5.81×10^{2}	7.37×10^{2}	9.59×10^{2}
	ECPSSR	1.89×10^{0}	1.18×10^{1}	3.75×10^{1}	8.66×10^{1}	1.66×10^{2}	2.80×10^{2}	4.34×10^{2}	6.30×10^{2}	8.70×10^{2}
$_{40}Zr$	Measured	2.85×10^{0}	1.56×10^{1}	3.63×10^{1}	8.44×10^{1}	1.37×10^{2}	1.95×10^{2}	2.70×10^{2}	3.23×10^{2}	4.35×10^{2}
	ECPSSR	3.74×10^{-1}	2.88×10^{0}	9.89×10^{0}	2.37×10^{1}	4.63×10^{1}	7.96×10^{1}	1.25×10^{2}	1.84×10^{2}	2.75×10^{2}
$_{47}Ag$	Measured	1.15×10^{-1}	1.18×10^{0}	3.63×10^{0}	1.11×10^{1}	2.10×10^{1}	3.92×10^{1}	4.69×10^{1}	7.79×10^{1}	9.68×10^{1}
	ECPSSR	3.99×10^{-2}	4.70×10^{-1}	1.94×10^{0}	5.11×10^{0}	1.06×10^{1}	1.89×10^{1}	3.06×10^{1}	4.60×10^{1}	6.56×10^{1}

Figure 20. Energy Dependence of the L-shell X-ray Production Cross Section for Be^+ Ions Incident upon Copper, Germanium, and Zirconium Targets



σ_{LX}(b)
BEAM ENERGY (MeV)
0
0.5
1.0
1.5
2.0
2.5
3.0
$_{29}$Cu
$_{32}$Ge
$_{40}$Zr
10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
5
2
First Born
ECPSSR
This Work

Figure 21. Energy Dependence of the L-shell X-ray Production Cross Section for Be^+ Ions Incident upon Zinc, Bromine, and Silver Targets

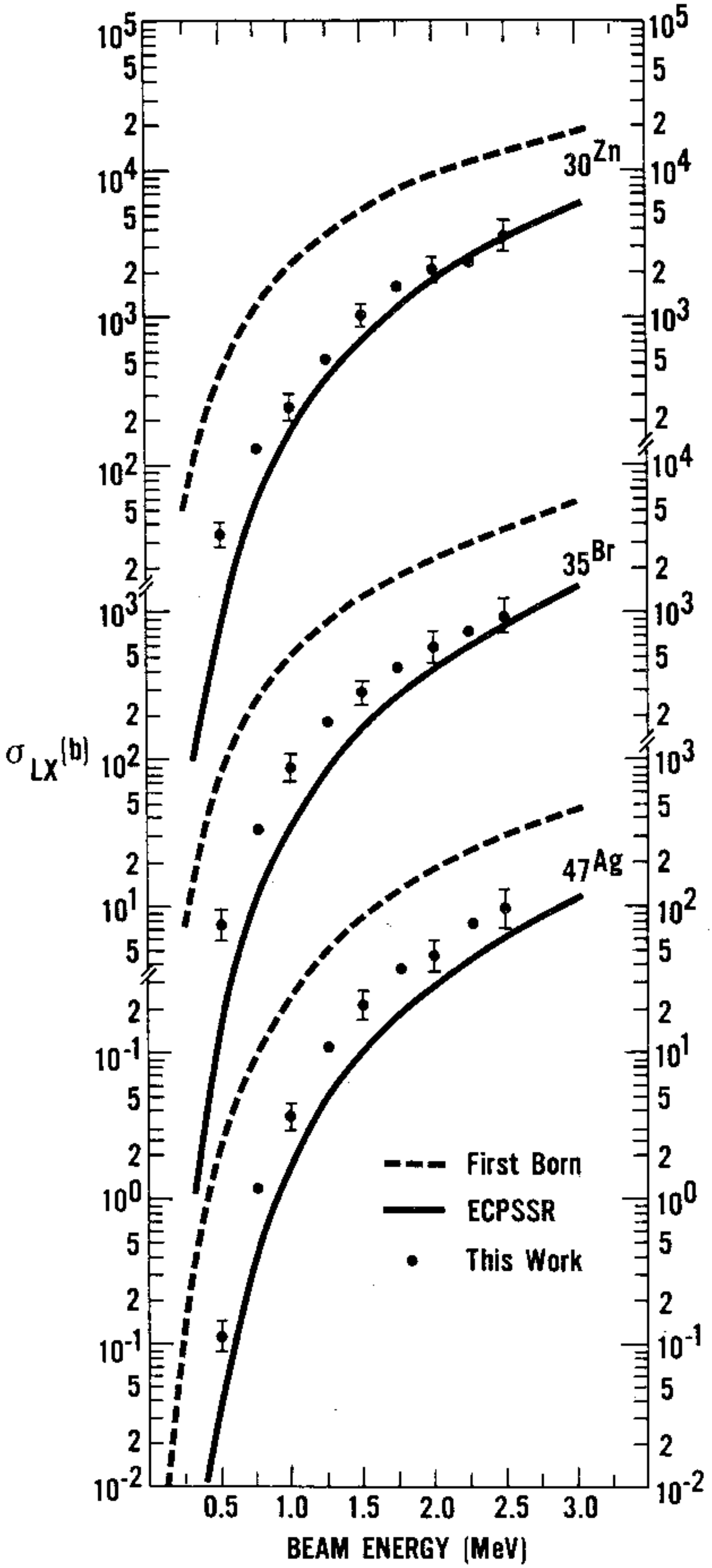
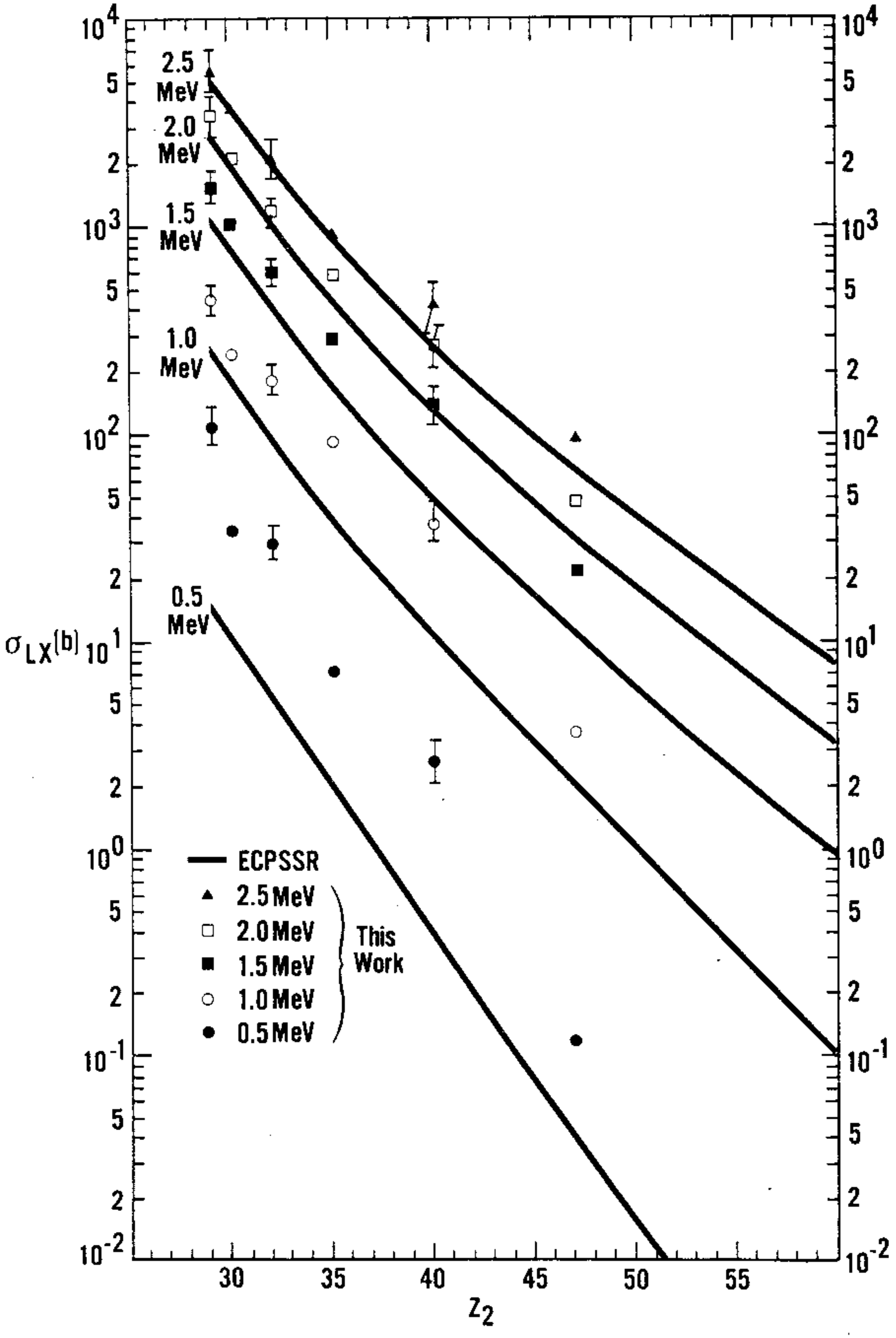

10^5
5
2
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
σ_{LX}(b)
$_{30}$Zn
$_{35}$Br
$_{47}$Ag
First Born
ECPSSR
This Work
0.5
1.0
1.5
2.0
2.5
3.0
BEAM ENERGY (MeV)

Figure 22. Target Atomic Number Dependence of the L-shell X-ray Production Cross Section for Be^+ Ions



$\sigma_{LX}(b)$
10^4
5
2
10^3
5
2
10^2
5
2
10^1
5
2
10^0
5
2
10^{-1}
5
2
10^{-2}
30
35
40
45
50
55
Z_2
2.5 MeV
2.0 MeV
1.5 MeV
1.0 MeV
0.5 MeV
ECPSSR
▲ 2.5 MeV
□ 2.0 MeV
■ 1.5 MeV
○ 1.0 MeV
● 0.5 MeV
This Work

bringing them more in line with the measured values. Again, it is difficult to determine the effect of any Coulomb deflection change.

M-shell Results

The measured total M-shell x-ray production cross sections for $^{9}_{4}Be^{+}$ ions incident upon thin $_{59}Pr$, $_{60}Nd$, $_{63}Eu$, $_{66}Dy$, $_{67}Ho$, $_{72}Hf$, $_{74}W$, $_{79}Au$, $_{82}Pb$, and $_{83}Bi$ are presented in Table VII along with the associated predictions of the ECPSSR theory. The results are also presented as a function of incident beam energy in Figures 23, 24, and 25 along with the predictions of both the ECPSSR (solid line) and the First Born (broken line) theories. Again, the First Born predictions overestimate the measured results while the ECPSSR values underestimate them. The low energy results show a significant discrepancy, while at high energy, the measured values and the ECPSSR predictions converge. Again, multiple ionization corrections will increase the theory estimates resulting in better agreement between the ECPSSR and measured values. Any Coulomb deflection factor corrections will affect the low energy results more than the high but it is still rather difficult to predict the exact effect.

Figure 26 presents the measured values and the ECPSSR predictions as a function of target atomic number (Z_2). There is a significant discrepancy at low energy which

TABLE VII

M-SHELL X-RAY PRODUCTION CROSS SECTIONS (BARNS) FOR INCIDENT $^{9}_{4}Be^{+}$ IONS

		BEAM ENERGY (MeV)								
Target		0.5	0.75	1.0	1.25	1.5	1.75	2.0	2.25	2.5
59^{Pr}	Measured	1.75×10^{2}	4.01×10^{2}	7.69×10^{2}	1.20×10^{3}	2.37×10^{3}	3.10×10^{3}	3.93×10^{3}	4.33×10^{3}	4.92×10^{3}
	ECPSSR	1.06×10^{1}	6.39×10^{1}	2.01×10^{2}	4.47×10^{2}	7.87×10^{2}	1.21×10^{3}	1.70×10^{3}	2.24×10^{3}	2.81×10^{3}
60^{Nd}	Measured	1.50×10^{2}	4.73×10^{2}	7.81×10^{2}	1.53×10^{3}	1.66×10^{3}	2.41×10^{3}	3.05×10^{3}	4.67×10^{3}	7.55×10^{3}
	ECPSSR	1.12×10^{1}	6.63×10^{1}	2.07×10^{2}	4.62×10^{2}	8.17×10^{2}	1.27×10^{3}	1.79×10^{3}	2.37×10^{3}	2.99×10^{3}
63^{Eu}	Measured	1.01×10^{2}	3.12×10^{2}	5.48×10^{2}	9.80×10^{2}	1.48×10^{3}	1.78×10^{3}	2.83×10^{3}	3.01×10^{3}	4.44×10^{3}
	ECPSSR	8.57×10^{0}	5.45×10^{1}	1.77×10^{2}	4.05×10^{2}	7.51×10^{2}	1.19×10^{3}	1.72×10^{3}	2.31×10^{3}	2.96×10^{3}
66^{Dy}	Measured	7.52×10^{1}	2.57×10^{2}	4.69×10^{2}	8.64×10^{2}	1.38×10^{3}	1.70×10^{3}	2.29×10^{3}	2.70×10^{3}	3.93×10^{3}
	ECPSSR	6.18×10^{0}	4.22×10^{1}	1.40×10^{2}	3.30×10^{2}	6.29×10^{2}	1.02×10^{3}	1.50×10^{3}	2.05×10^{3}	2.67×10^{3}
67^{Ho}	Measured	5.51×10^{1}	2.40×10^{2}	4.73×10^{2}	7.05×10^{2}	1.01×10^{3}	1.43×10^{3}	1.79×10^{3}	2.34×10^{3}	3.41×10^{3}
	ECPSSR	5.42×10^{0}	3.80×10^{1}	1.27×10^{2}	3.02×10^{2}	5.78×10^{2}	9.52×10^{2}	1.40×10^{3}	1.93×10^{3}	2.52×10^{3}
72^{Hf}	Measured	3.10×10^{1}	1.28×10^{2}	2.64×10^{2}	5.02×10^{2}	7.96×10^{2}	1.09×10^{3}	1.36×10^{3}	1.70×10^{3}	2.83×10^{3}
	ECPSSR	2.58×10^{0}	2.16×10^{1}	7.66×10^{1}	1.88×10^{2}	3.73×10^{2}	6.38×10^{2}	9.84×10^{2}	1.38×10^{3}	1.85×10^{3}
74^{W}	Measured	2.68×10^{1}	1.48×10^{2}	3.29×10^{2}	6.58×10^{2}	9.15×10^{2}	1.46×10^{3}	1.88×10^{3}	2.43×10^{3}	3.13×10^{3}
	ECPSSR	1.66×10^{0}	1.53×10^{1}	5.57×10^{1}	1.39×10^{2}	2.78×10^{2}	4.82×10^{2}	7.55×10^{2}	1.08×10^{3}	1.46×10^{3}
79^{Au}	Measured	6.54×10^{0}	4.20×10^{1}	1.20×10^{2}	2.45×10^{2}	4.06×10^{2}	5.81×10^{2}	7.73×10^{2}	9.62×10^{2}	1.25×10^{2}
	ECPSSR	4.99×10^{-1}	5.90×10^{0}	2.34×10^{1}	6.06×10^{1}	1.25×10^{2}	2.22×10^{2}	3.56×10^{2}	5.29×10^{2}	7.39×10^{2}
82^{Pb}	Measured	2.69×10^{0}	2.37×10^{1}	7.77×10^{1}	1.46×10^{2}	2.50×10^{2}	3.66×10^{2}	5.01×10^{2}	6.51×10^{2}	9.73×10^{2}
	ECPSSR	2.28×10^{-1}	3.30×10^{0}	1.41×10^{1}	3.78×10^{1}	7.95×10^{1}	1.44×10^{2}	2.34×10^{2}	3.52×10^{2}	5.00×10^{2}
83^{Bi}	Measured	2.34×10^{0}	2.17×10^{1}	5.85×10^{1}	1.37×10^{2}	2.41×10^{2}	3.75×10^{2}	5.12×10^{2}	6.29×10^{2}	8.60×10^{2}
	ECPSSR	1.74×10^{-1}	2.70×10^{0}	1.19×10^{1}	3.22×10^{1}	6.83×10^{1}	1.24×10^{2}	2.04×10^{2}	3.08×10^{2}	4.38×10^{2}

Figure 23. Energy Dependence of the M-shell X-ray Production Cross Section for Be^+ Ions Incident upon Praseodymium, Dysprosium, Hafnium, and Bismuth Targets

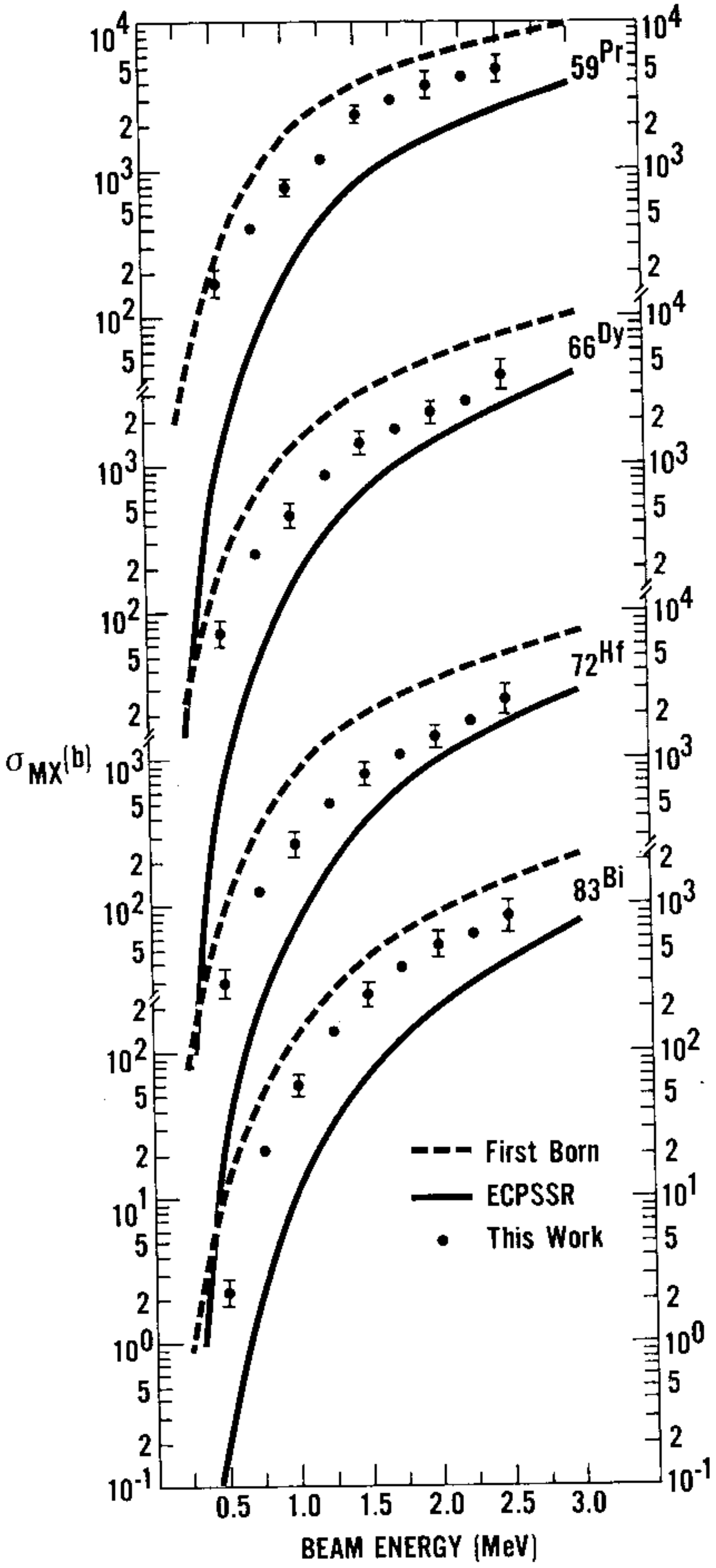

59^{Pr}
66^{Dy}
72^{Hf}
83^{Bi}
σ_{MX}(b)
10^4
10^3
10^2
10^1
10^0
10^{-1}
0.5
1.0
1.5
2.0
2.5
3.0
BEAM ENERGY (MeV)
First Born
ECPSSR
This Work

Figure 24. Energy Dependence of the M-shell X-ray Production Cross Section for Be^+ Ions Incident upon Neodymium, Holmium, and Gold Targets

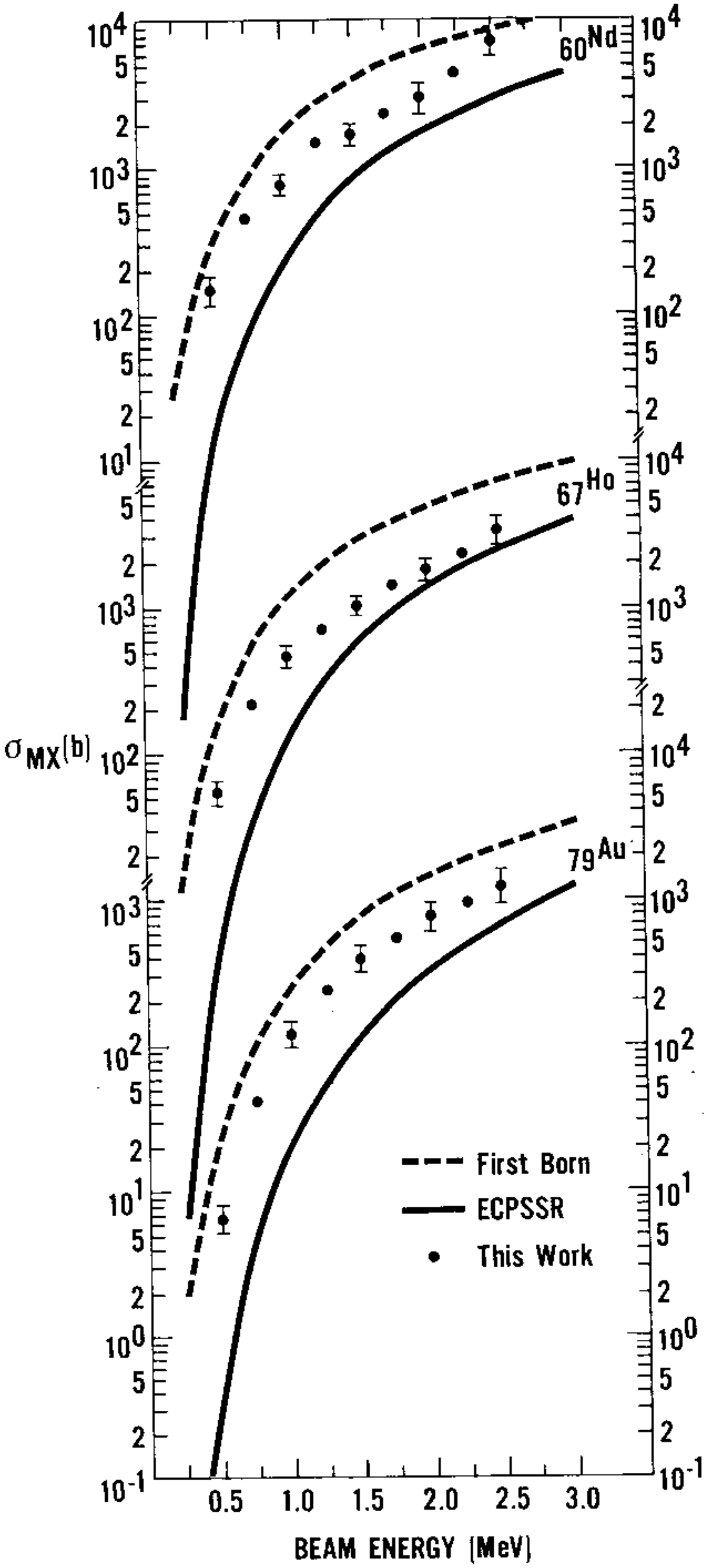
σ_{MX}(b)
10^4
10^3
10^2
10^1
10^0
10^{-1}
5
2
$_{60}$Nd
$_{67}$Ho
$_{79}$Au
0.5
1.0
1.5
2.0
2.5
3.0
BEAM ENERGY (MeV)
First Born
ECPSSR
This Work

Figure 25. Energy Dependence of the M-shell X-ray Production Cross Section for Be^+ Ions Incident upon Europium, Tungsten, and Lead Targets

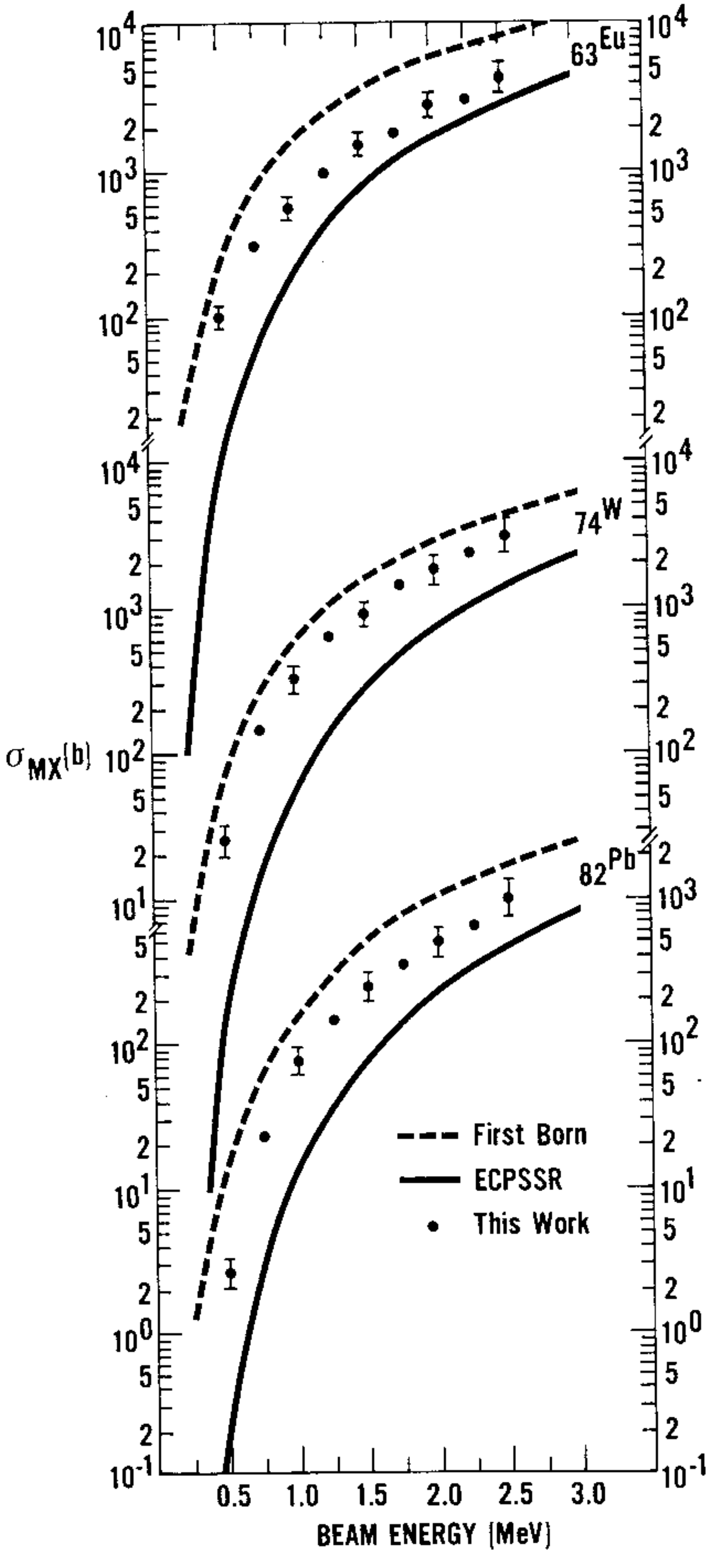
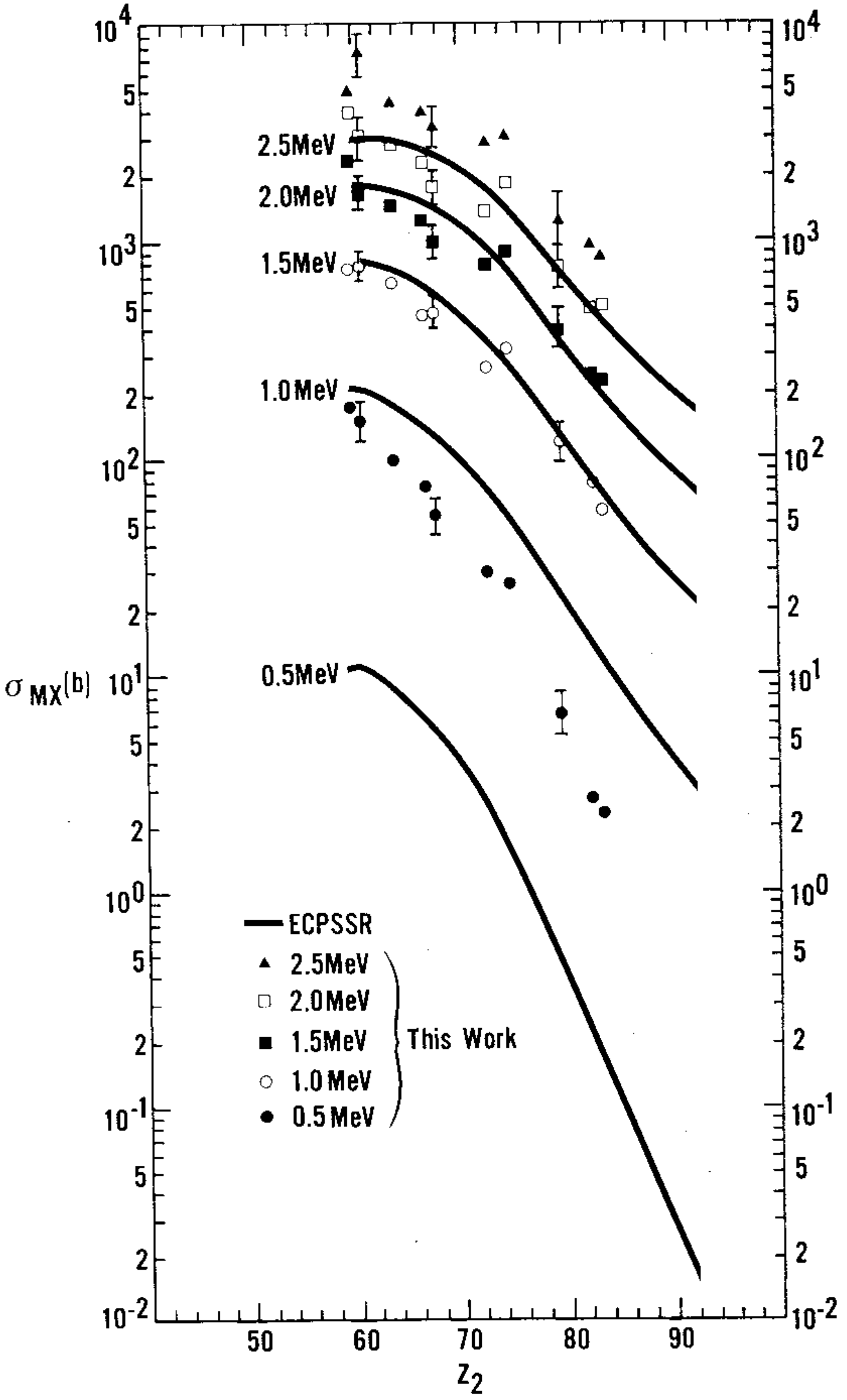

σ_{MX}(b)
$_{63}$Eu
$_{74}$W
$_{82}$Pb
10^4
10^3
10^2
10^1
10^0
10^{-1}
5
2
First Born
ECPSSR
This Work
0.5
1.0
1.5
2.0
2.5
3.0
BEAM ENERGY (MeV)

Figure 26. Target Atomic Number Dependence of the M-shell X-ray Production Cross Section for Be^+ Ions



10^4
5
2
10^3
5
2
10^2
5
2
$\sigma_{MX}(b)$ 10^1
5
2
10^0
5
2
10^{-1}
5
2
10^{-2}
50
60
70
80
90
Z_2
2.5MeV
2.0MeV
1.5MeV
1.0MeV
0.5MeV
ECPSSR
▲ 2.5MeV
□ 2.0MeV
■ 1.5MeV
○ 1.0MeV
● 0.5MeV
This Work

appears to be independent of Z_2. The prediction of the ECPSSR theory does accurately predict the trend of the data as a function of the target atomic number. Although multiple ionization in K- and L-shells is very small, the probability for multiple ionization in the N- and higher shells is significantly greater. This will cause only a slight shift in the x-ray energy lines but a substantial change in the Coster-Kronig and Auger transition probabilities yielding an increased fluorescence yield. This increase could be substantial and account for much of the difference between the ECPSSR theory and the measured values.

$^{27}Al^+$ DATA

The x-ray production cross section measurements for incident $^{27}_{13}Al^+$ ions is presented here. The results are presented in two groups: (i) L-shell results and (ii) M-shell results.

L-shell Results

The measured total L-shell x-ray production cross sections for $^{27}_{13}Al^+$ ions incident upon thin solid $_{28}Ni$, $_{29}Cu$, $_{30}Zn$, $_{33}As$, $_{40}Zr$, and $_{46}Pd$ targets are presented in Table VIII. The predictions of the First Born and the ECPSSR theories are given in Appendix D. The measured results are presented as a function of incident beam energy

TABLE VIII

MEASURED L-SHELL X-RAY PRODUCTION CROSS SECTIONS (BARNS) FOR INCIDENT $^{27}_{13}Al^{+}$ IONS

BEAM ENERGY (MeV)

Target	1.25	1.5	1.75	2.0	2.25
$_{28}$Ni	1.5×10^{4}	1.85×10^{4}	2.25×10^{4}	2.45×10^{4}	2.31×10^{4}
$_{29}$Cu	1.03×10^{4}	1.15×10^{4}	1.30×10^{4}	1.58×10^{4}	1.86×10^{4}
$_{30}$Zn	8.37×10^{3}	1.02×10^{4}	1.11×10^{4}	1.40×10^{4}	1.64×10^{4}
$_{33}$As	4.74×10^{3}	7.29×10^{3}	7.87×10^{3}	9.49×10^{3}	8.97×10^{3}
$_{40}$Zr	5.19×10^{2}	6.30×10^{2}	9.17×10^{2}	2.12×10^{3}	1.38×10^{4}
$_{46}$Pd	9.61×10^{0}	1.39×10^{1}	1.42×10^{1}	6.84×10^{1}	1.49×10^{2}

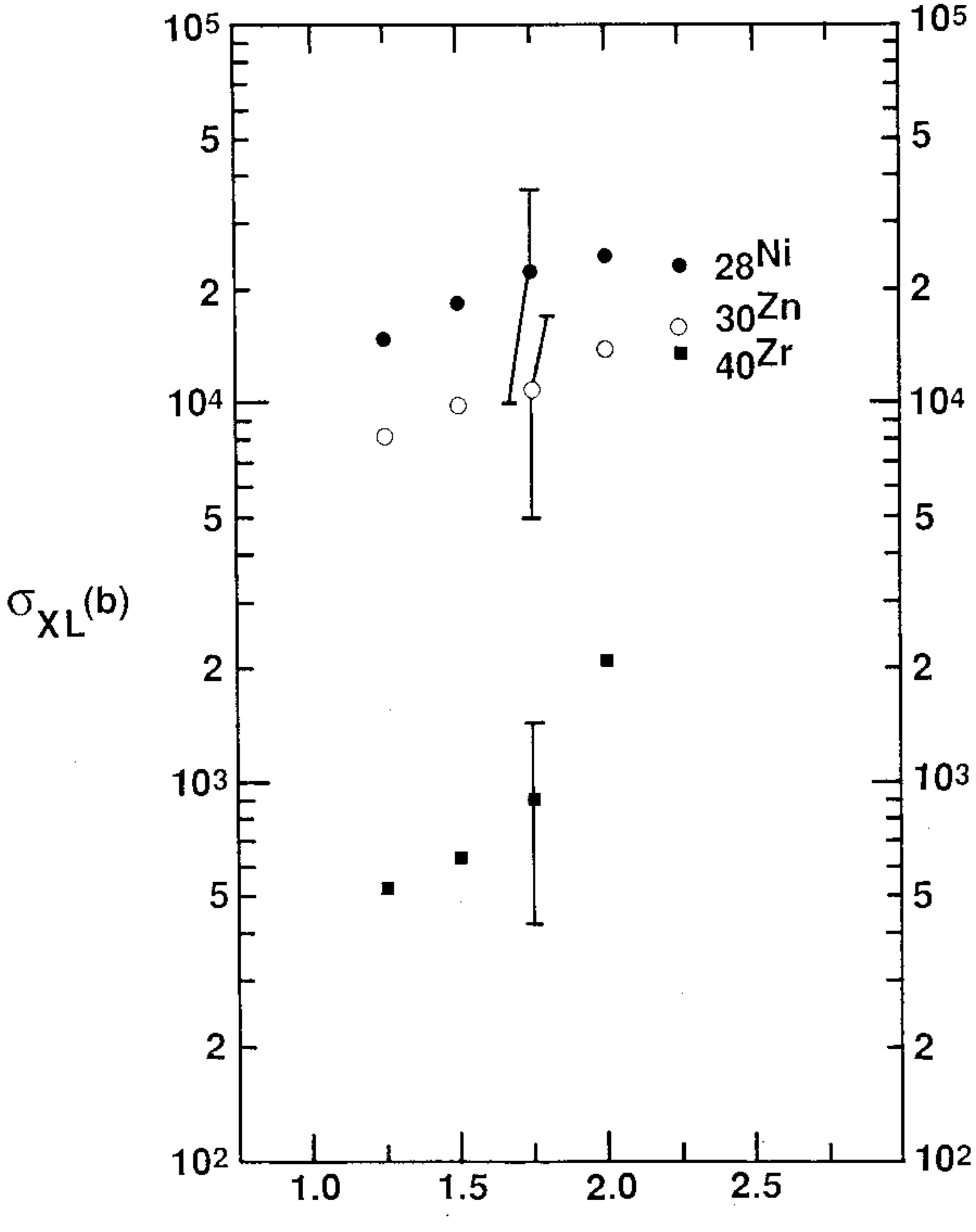
in Figures 27 and 28. The predictions of the theories are not shown in the figures because of the substantial differences involved (see Appendix D). The theories do not predict the data very well anywhere nor should they be expected to since the measurements are at an incident velocity which is very much lower than the limits for either the ECPSSR or the First Born theories. The only prediction of the theories which tends to be supported is that the measured results should increase with increasing energy although the rate of increase is not even properly predicted.

Figure 29 shows the L-shell x-ray production cross sections as a function of Z_2 for a typical beam energy of 1.5 MeV. The First Born theory is also presented to show how much in error the theories are. The ECPSSR theory is another factor of 10^3 to 10^5 below the First Born. Again, no correlation between data and theory can be drawn except that the theories predict a decrease in the cross section as Z_2 increases although the rate of decrease is not accurately predicted. The results demonstrate that the ECPSSR and First Born theories need substantial revisions in order to extend their range to such low ($V_1 < 0.01\ V_e$) velocities.

M-shell Results

The total measured M-shell x-ray production cross sections for ${}^{27}_{13}Al^+$ ions incident upon thin solid ${}_{59}Pr$, ${}_{60}Nd$,

Figure 27. Energy Dependence of the L-shell X-ray Production Cross Section for Al^+ Ions Incident upon Nickel, Zinc, and Zirconium Targets



10^5
5
2
10^4
5
2
10^3
5
2
10^2
$\sigma_{XL}(b)$
● $_{28}Ni$
○ $_{30}Zn$
■ $_{40}Zr$
1.0
1.5
2.0
2.5
BEAM ENERGY (MeV)

Figure 28. Energy Dependence of the L-shell X-ray Production Cross Section for Al^+ Ions Incident upon Copper, Arsenic, and Palladium Targets

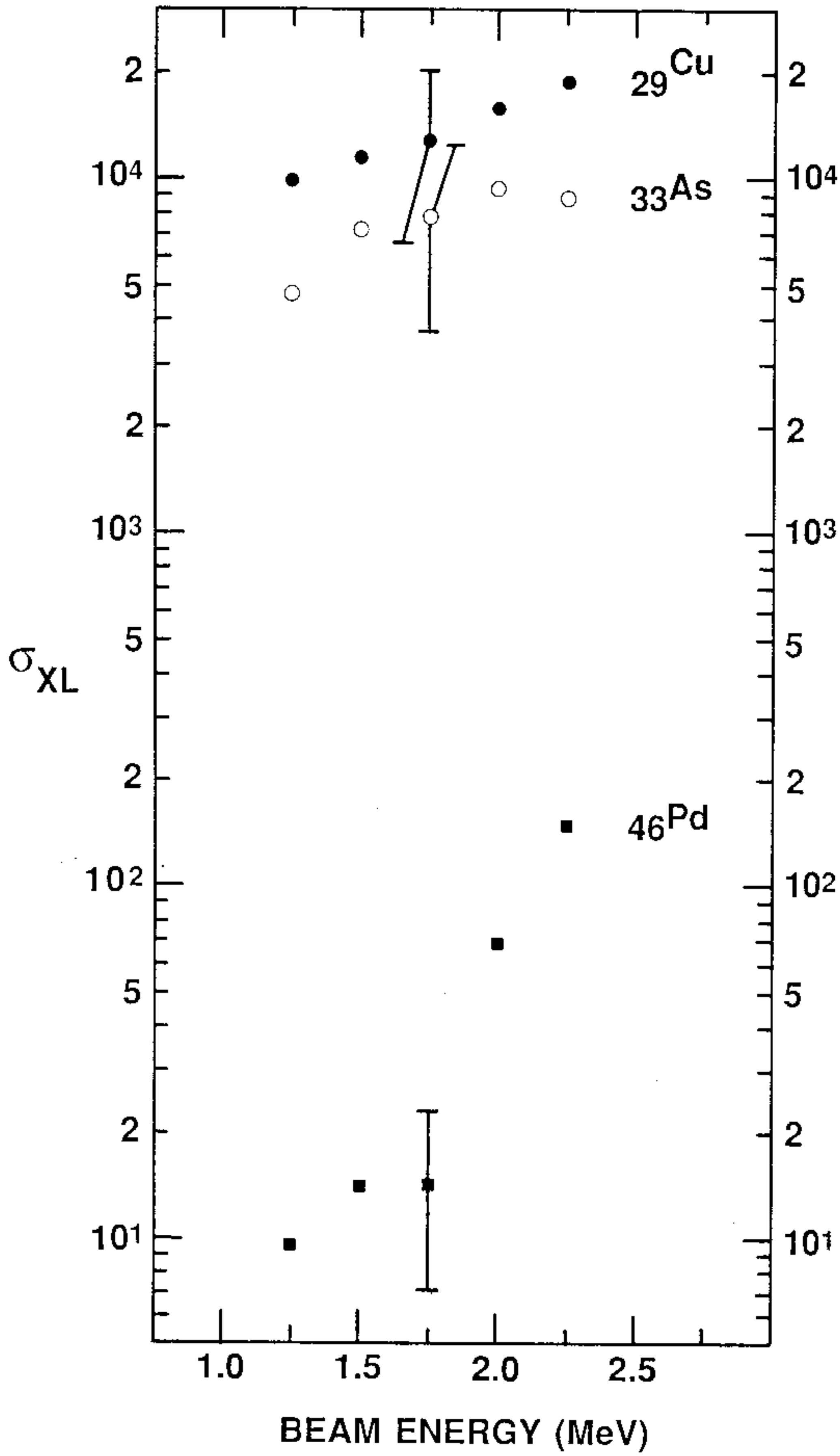
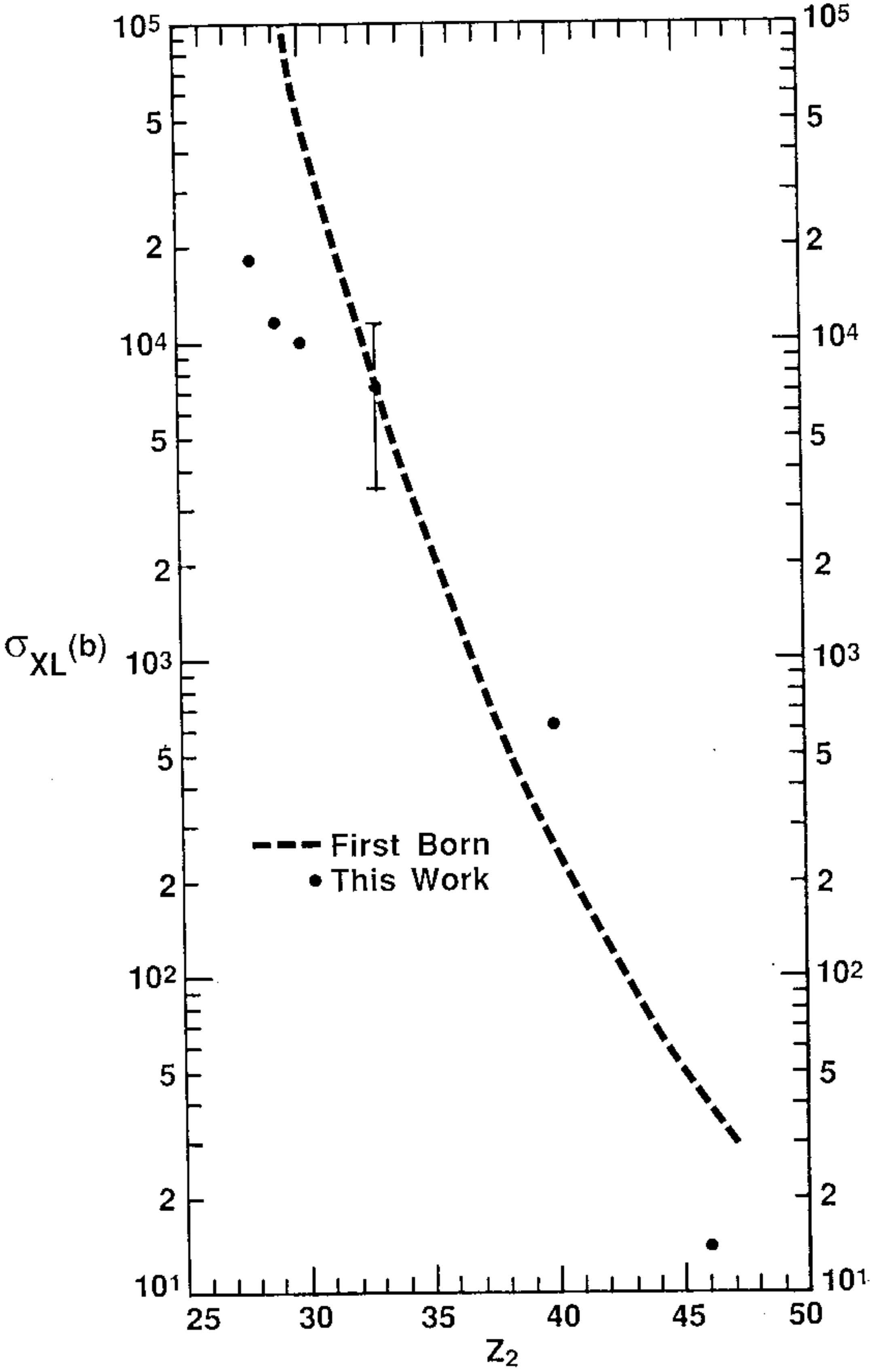

$_{29}$Cu
$_{33}$As
$_{46}$Pd
σ_{XL}
2
10^4
5
2
10^3
5
2
10^2
5
2
10^1
1.0
1.5
2.0
2.5
BEAM ENERGY (MeV)

Figure 29. Target Atomic Number Dependence of the L-shell X-ray Production Cross Section for Al^+ Ions



10^5
5
2
10^4
5
2
$\sigma_{XL}(b)$
10^3
5
2
10^2
5
2
10^1
First Born
This Work
25
30
35
40
45
50
Z_2

$_{64}$Gd, $_{66}$Dy, $_{71}$Lu, $_{72}$Hf, $_{79}$Au, $_{82}$Pb, $_{83}$Bi, and $_{92}$U targets are presented in Table IX. The predictions of the First Born and ECPSSR theories are listed in Appendix E. The measured results and the First Born prediction are presented as a function of incident ion energy in figures 30, 31 and 32. Again, the theories do not predict the data very well. The ECPSSR predictions are even factors of 10^3 to 10^{11} below the First Born. The trends or shapes of the curve do not predict the measured results for the lower Z_2 targets. The shapes of the curves begin to reflect the shapes predicted by the theory for higher Z_2 (Au, Pb, Bi, and U) with U being predicted rather well by the First Born. This trend is somewhat puzzling since, although there is an expectation that the theories should fit better at lower Z_1/Z_2 ratios, the ECPSSR theory has its greatest discrepancy (especially for low energy) here than at the lower Z_2 targets. Since the First Born and ECPSSR are similar in their initial assumptions, one must conclude that the problem lies in the Coulomb deflection term for low energy corrections which the First Born does not include. This correction term appears to reduce the cross-section by too large an amount and may need some revisions in this regard.

Figure 33 shows the M-shell x-ray production cross sections as a function of incident target atomic number (Z_2), the results of which are similar to that for the L-shell in Figure 29. Again, the only correlation between

TABLE IX

MEASURED M-SHELL X-RAY PRODUCTION CROSS SECTIONS (BARNS) FOR INCIDENT ${}^{27}_{13}\mathrm{Al}^{+}$ IONS

BEAM ENERGY (MeV)

Target	0.5	0.75	1.0	1.25	1.5	1.75	2.0	2.25
${}_{59}\mathrm{Pr}$	$2.89\text{x}10^{3}$	$6.11\text{x}10^{3}$	$6.91\text{x}10^{3}$	$8.38\text{x}10^{3}$	$1.07\text{x}10^{4}$	$1.48\text{x}10^{4}$	$1.66\text{x}10^{4}$	$3.07\text{x}10^{4}$
${}_{60}\mathrm{Nd}$	$7.42\text{x}10^{3}$	$1.49\text{x}10^{4}$	$1.98\text{x}10^{4}$	$2.34\text{x}10^{4}$	$2.03\text{x}10^{4}$	$3.87\text{x}10^{4}$	$3.06\text{x}10^{4}$	$4.37\text{x}10^{4}$
${}_{64}\mathrm{Gd}$	$4.69\text{x}10^{3}$	$9.07\text{x}10^{3}$	$1.11\text{x}10^{4}$	$1.42\text{x}10^{4}$	$1.55\text{x}10^{4}$	$1.78\text{x}10^{4}$	$1.98\text{x}10^{4}$	$2.13\text{x}10^{4}$
${}_{66}\mathrm{Dy}$	$4.76\text{x}10^{3}$	$9.31\text{x}10^{3}$	$1.13\text{x}10^{4}$	$1.27\text{x}10^{4}$	$1.47\text{x}10^{4}$	$1.68\text{x}10^{4}$	$2.22\text{x}10^{4}$	$2.04\text{x}10^{4}$
${}_{71}\mathrm{Lu}$	$2.92\text{x}10^{3}$	$6.19\text{x}10^{3}$	$1.14\text{x}10^{4}$	$1.64\text{x}10^{4}$	$1.70\text{x}10^{4}$	$1.77\text{x}10^{4}$	$2.09\text{x}10^{4}$	$1.93\text{x}10^{4}$
${}_{72}\mathrm{Hf}$	$1.48\text{x}10^{3}$	$4.33\text{x}10^{3}$	$7.64\text{x}10^{3}$	$1.06\text{x}10^{4}$	$1.13\text{x}10^{4}$	$1.35\text{x}10^{4}$	$1.40\text{x}10^{4}$	$1.50\text{x}10^{4}$
${}_{79}\mathrm{Au}$	$3.70\text{x}10^{2}$	$1.04\text{x}10^{3}$	$2.27\text{x}10^{3}$	$3.53\text{x}10^{3}$	$4.25\text{x}10^{3}$	$5.75\text{x}10^{3}$	$5.70\text{x}10^{3}$	$6.13\text{x}10^{3}$
${}_{82}\mathrm{Pb}$	$9.66\text{x}10^{1}$	$2.87\text{x}10^{2}$	$8.18\text{x}10^{2}$	$1.41\text{x}10^{3}$	$1.92\text{x}10^{3}$	$2.71\text{x}10^{3}$	$3.24\text{x}10^{3}$	$3.72\text{x}10^{3}$
${}_{83}\mathrm{Bi}$	$6.35\text{x}10^{1}$	$2.15\text{x}10^{2}$	$5.97\text{x}10^{2}$	$1.07\text{x}10^{3}$	$1.48\text{x}10^{3}$	$1.97\text{x}10^{3}$	$2.53\text{x}10^{3}$	$3.22\text{x}10^{3}$
${}_{92}\mathrm{U}$	---	$1.93\text{x}10^{0}$	$6.67\text{x}10^{0}$	$2.47\text{x}10^{1}$	$5.96\text{x}10^{1}$	$9.85\text{x}10^{1}$	$1.37\text{x}10^{2}$	$1.88\text{x}10^{2}$

Figure 30. Energy Dependence of the M-shell X-ray Production Cross Section for Al^+ Ions Incident upon Praseodymium, Dysprosium, Gold, and Uranium Targets

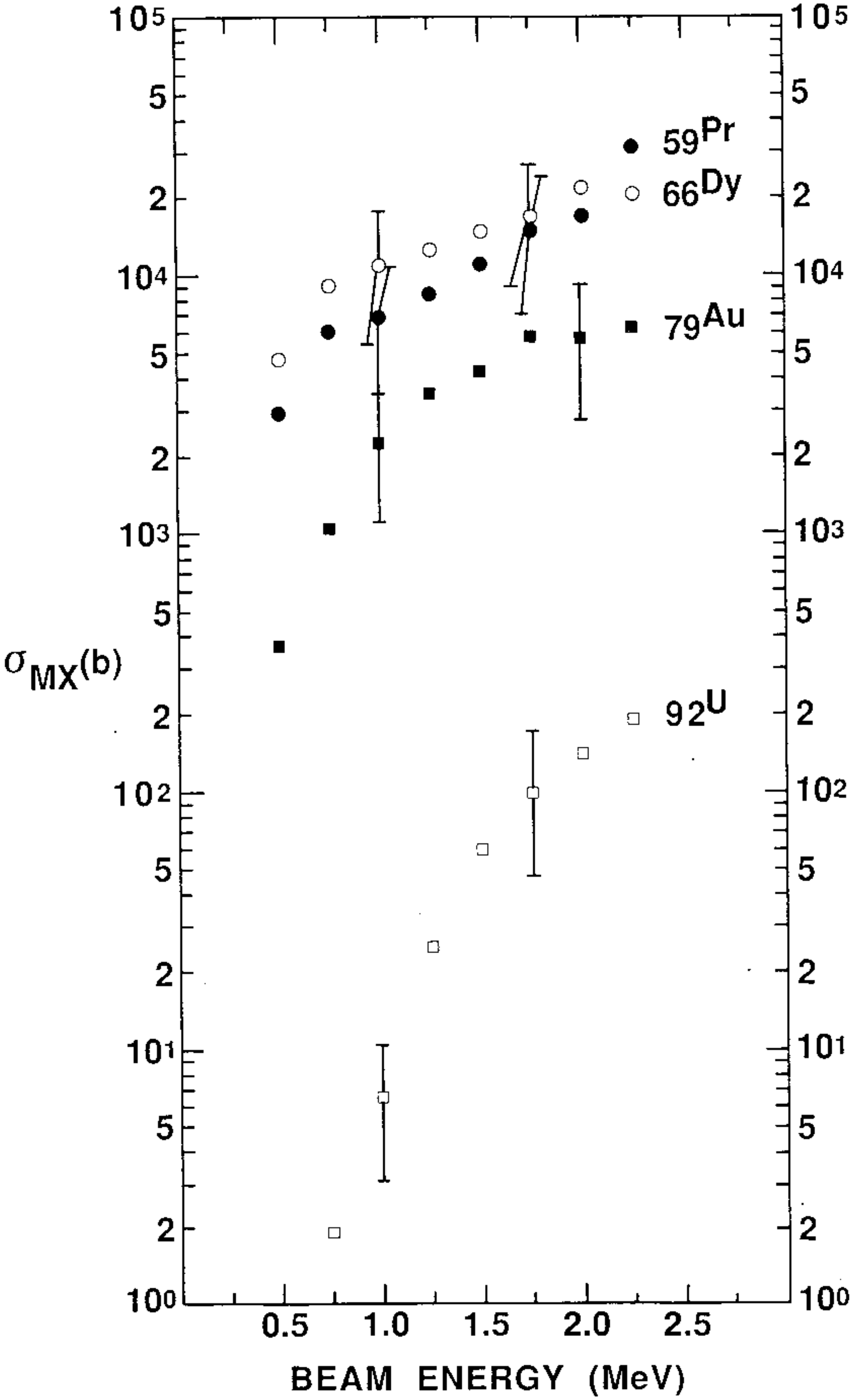

10^5
5
2
10^4
5
2
10^3
5
σ_{MX}(b)
2
10^2
5
2
10^1
5
2
10^0
$_{59}$Pr
$_{66}$Dy
$_{79}$Au
$_{92}$U
0.5
1.0
1.5
2.0
2.5
BEAM ENERGY (MeV)

Figure 31. Energy Dependence of the M-shell X-ray Production Cross Section for Al^+ Ions Incident upon Neodymium, Lutetium, and Lead Targets

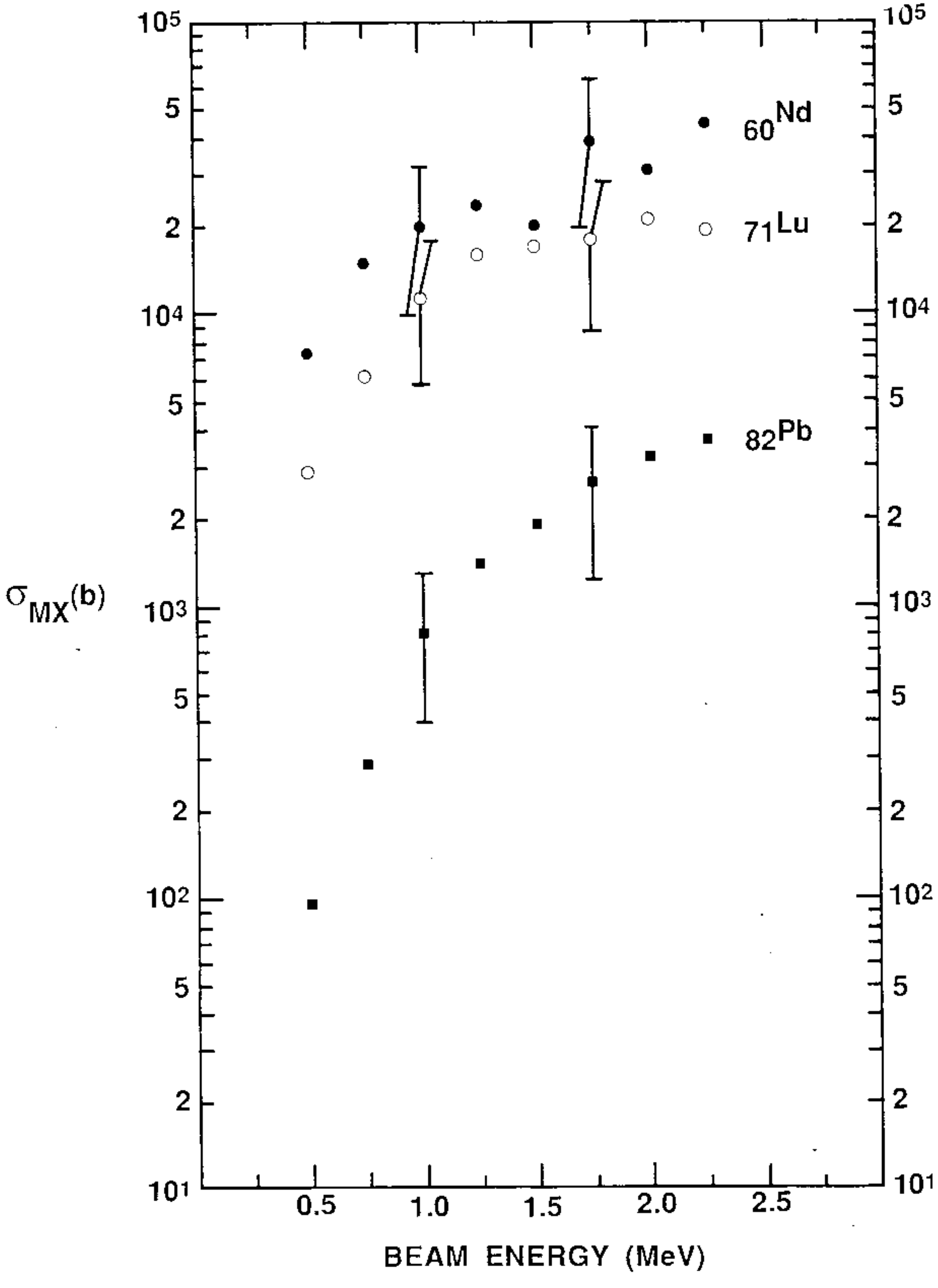
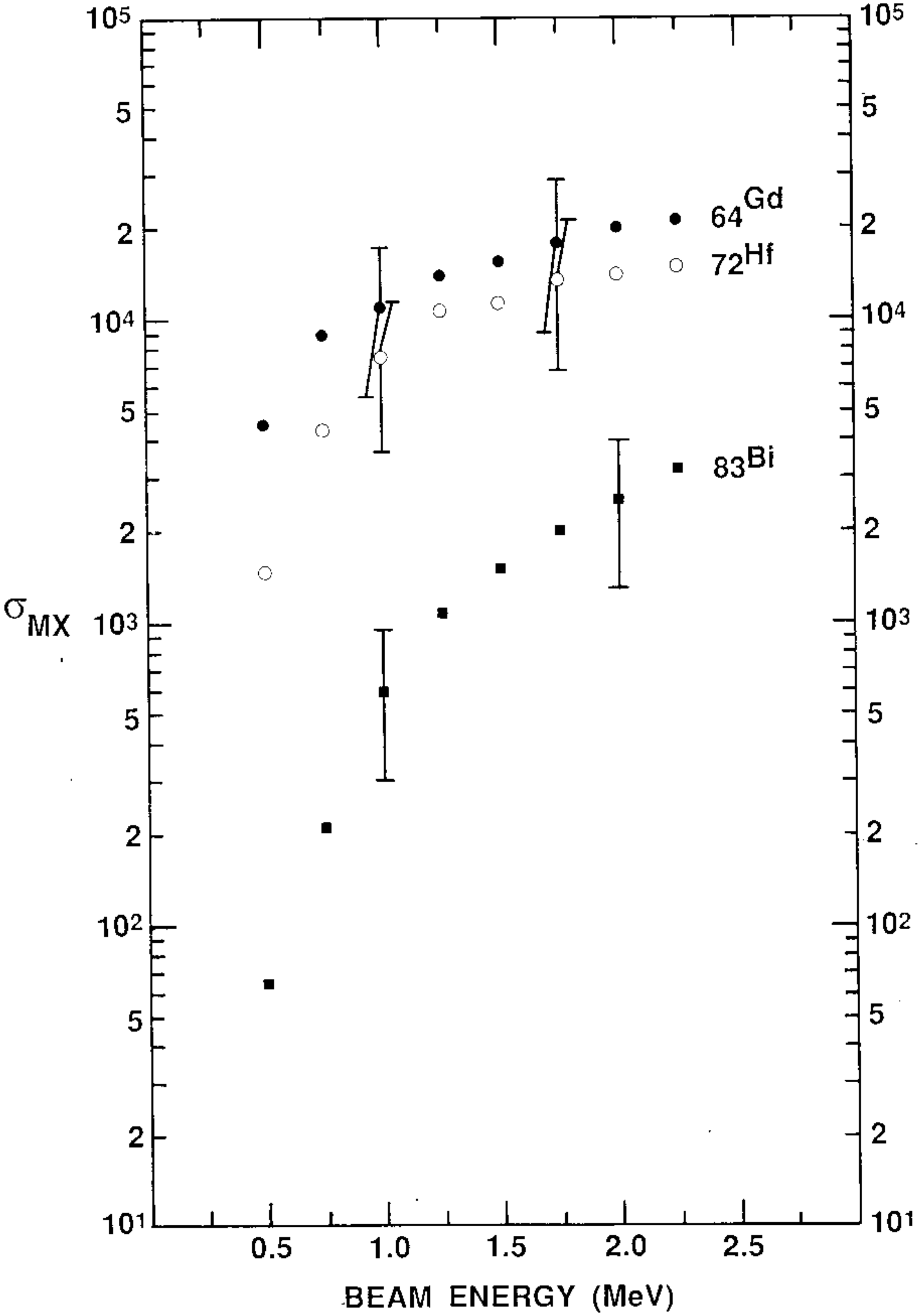
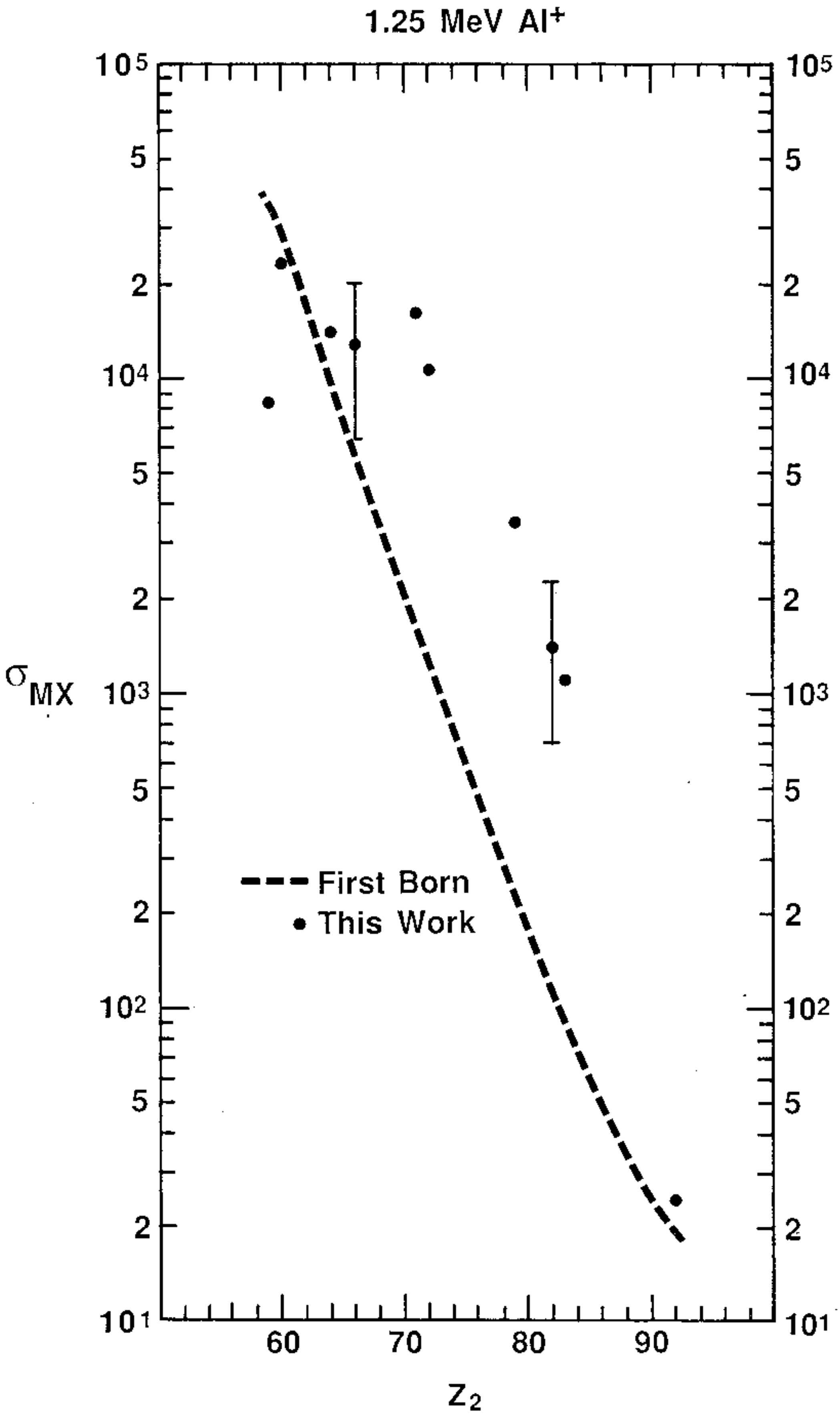

10⁵
5
2
10⁴
5
2
10³
5
2
10²
5
2
10¹
σMX(b)
60Nd
71Lu
82Pb
0.5
1.0
1.5
2.0
2.5
BEAM ENERGY (MeV)

Figure 32. Energy Dependence of the M-shell X-ray Production Cross Section for Al^+ Ions Incident upon Gadolinium, Hafnium, and Bismuth Targets



σ_{MX}
10^5
5
2
10^4
5
2
10^3
5
2
10^2
5
2
10^1
0.5
1.0
1.5
2.0
2.5
BEAM ENERGY (MeV)
● $_{64}$Gd
○ $_{72}$Hf
■ $_{83}$Bi

Figure 33. Target Atomic Number Dependence of the M-shell X-ray Production Cross Sections for Al^+ Ions


1.25 MeV Al⁺
10⁵
5
2
10⁴
5
2
σ_MX
10³
5
2
10²
5
2
10¹
60
70
80
90
Z₂
First Born
This Work

data and the theories is the general trend to lower cross section for higher Z_2 but the rate of decrease is in error. Again, the better agreement is being predicted for higher Z_2 than lower, but only for the First Born (also see Appendix E).

^{40}Ar Data

The x-ray production cross section for incident $^{40}_{18}Ar^+$ ions are presented here. Only M-shell results were examined as the backscatter spectrum was difficult to analyze for any lower Z_2 targets.

M-shell Results

The measured M-shell x-ray production cross sections for $^{40}Ar^+$ ions incident upon thin solid $_{59}Pr$, $_{60}Nd$, $_{64}Gd$, $_{66}Dy$, $_{71}Lu$, $_{72}Hf$, $_{79}Au$, $_{82}Pb$, and $_{92}U$ targets are presented in Table X and shown as a function of incident ion energy in Figures 34, 35 and 36. The theories were so poor in their predictions that they are not shown in these figures but they are presented in Appendix F. The velocity ratio (v_1/v_e) is very small and the results should not be expected to agree with either the First Born or ECPSSR theories. The measured results are also presented as a function of target atomic number (Z_2) in figure 37. Also shown are the predictions of the First Born theory. The ECPSSR theory underpredicts the data even more, by factors of 10^4 to 10^{20}.

Again, one of the main problems appears to be the Coulomb deflection factor of the ECPSSR theory. It may be

TABLE X

MEASURED M-SHELL X-RAY PRODUCTION CROSS SECTIONS (BARNS) FOR INCIDENT $^{40}_{18}\mathrm{Ar}^{+}$ IONS

BEAM ENERGY (MeV)

Target	1.0	1.25	1.5	1.75	2.0
$_{59}$Pr	$5.12\mathrm{x}10^{3}$	$6.65\mathrm{x}10^{3}$	$1.28\mathrm{x}10^{4}$	$1.10\mathrm{x}10^{5}$	---
$_{60}$Nd	$1.10\mathrm{x}10^{4}$	$1.29\mathrm{x}10^{4}$	$1.59\mathrm{x}10^{4}$	$2.04\mathrm{x}10^{4}$	---
$_{64}$Gd	$8.08\mathrm{x}10^{3}$	$8.31\mathrm{x}10^{3}$	$1.10\mathrm{x}10^{4}$	$1.36\mathrm{x}10^{4}$	$1.28\mathrm{x}10^{4}$
$_{66}$Dy	$7.82\mathrm{x}10^{3}$	$9.41\mathrm{x}10^{3}$	$1.00\mathrm{x}10^{4}$	$1.19\mathrm{x}10^{4}$	$1.32\mathrm{x}10^{4}$
$_{71}$Lu	$4.71\mathrm{x}10^{3}$	$5.79\mathrm{x}10^{3}$	$9.00\mathrm{x}10^{3}$	$9.26\mathrm{x}10^{3}$	$1.30\mathrm{x}10^{4}$
$_{72}$Hf	$2.47\mathrm{x}10^{3}$	$4.32\mathrm{x}10^{3}$	$7.94\mathrm{x}10^{3}$	$7.32\mathrm{x}10^{3}$	$8.99\mathrm{x}10^{3}$
$_{79}$Au	$1.05\mathrm{x}10^{3}$	$1.85\mathrm{x}10^{3}$	$2.00\mathrm{x}10^{3}$	$2.89\mathrm{x}10^{3}$	$3.24\mathrm{x}10^{3}$
$_{83}$Bi	---	---	---	---	$2.41\mathrm{x}10^{3}$
$_{92}$U	$9.81\mathrm{x}10^{1}$	$1.74\mathrm{x}10^{2}$	$3.49\mathrm{x}10^{2}$	$5.65\mathrm{x}10^{2}$	$8.98\mathrm{x}10^{2}$
$_{82}$Pb	$7.01 \mathrm{x} 10^{2}$	$1.10 \mathrm{x} 10^{3}$	$1.55\mathrm{x}10^{3}$	$2.91 \mathrm{x} 10^{3}$	$4.17\mathrm{x}10^{3}$

Figure 34. Energy Dependence of the M-shell X-ray Production Cross Section for Ar^+ Ions Incident upon Praseodymium, Dysprosium, and Gold Targets

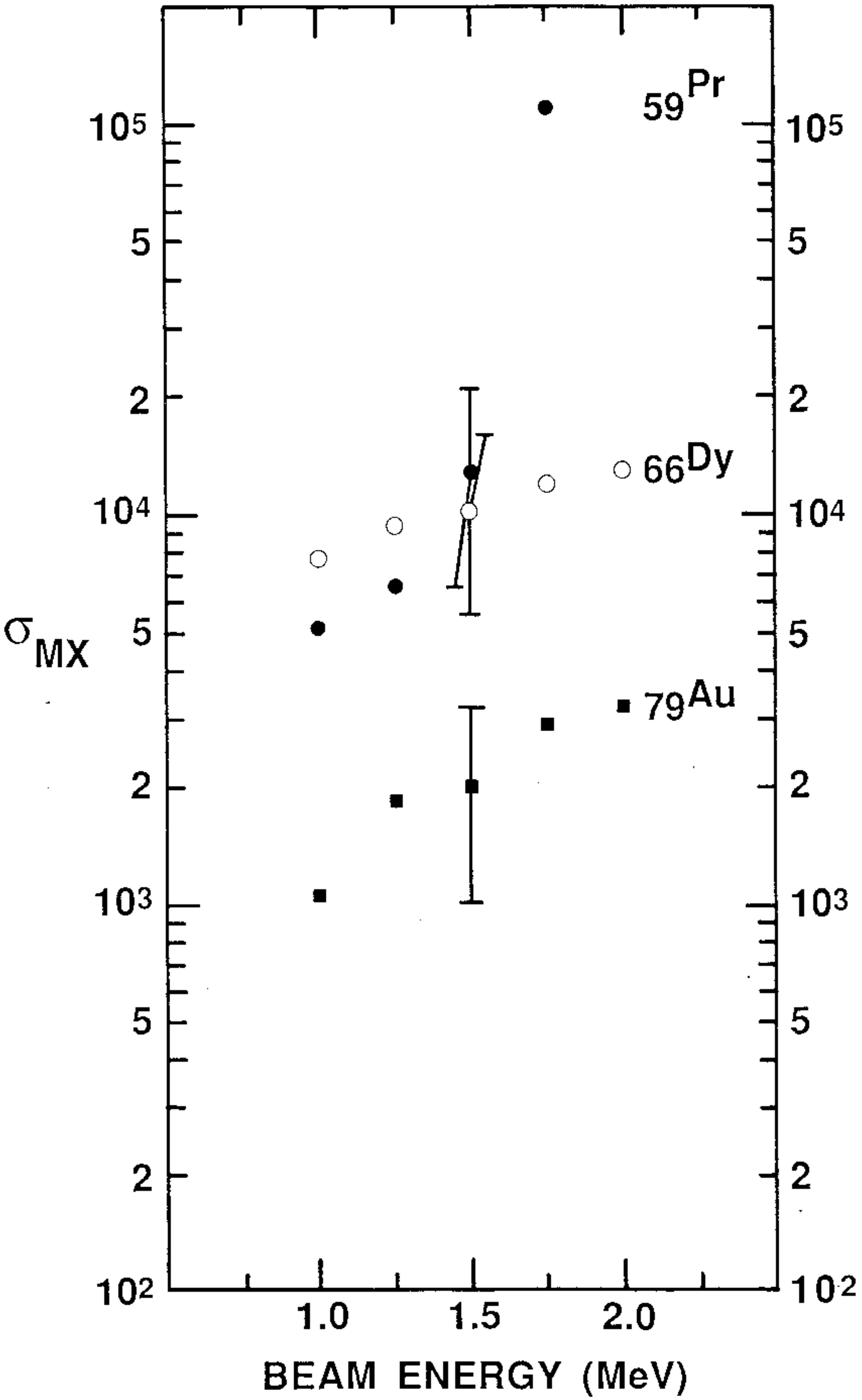

59^{Pr}
66^{Dy}
79^{Au}
σ_{MX}
10^5
5
2
10^4
5
2
10^3
5
2
10^2
10^5
5
2
10^4
5
2
10^3
5
2
$10^{\cdot 2}$
1.0
1.5
2.0
BEAM ENERGY (MeV)

Figure 35. Energy Dependence of the M-shell X-ray Production Cross Section for Ar^+ Ions Incident upon Neodymium, Lutetium, and Lead Targets

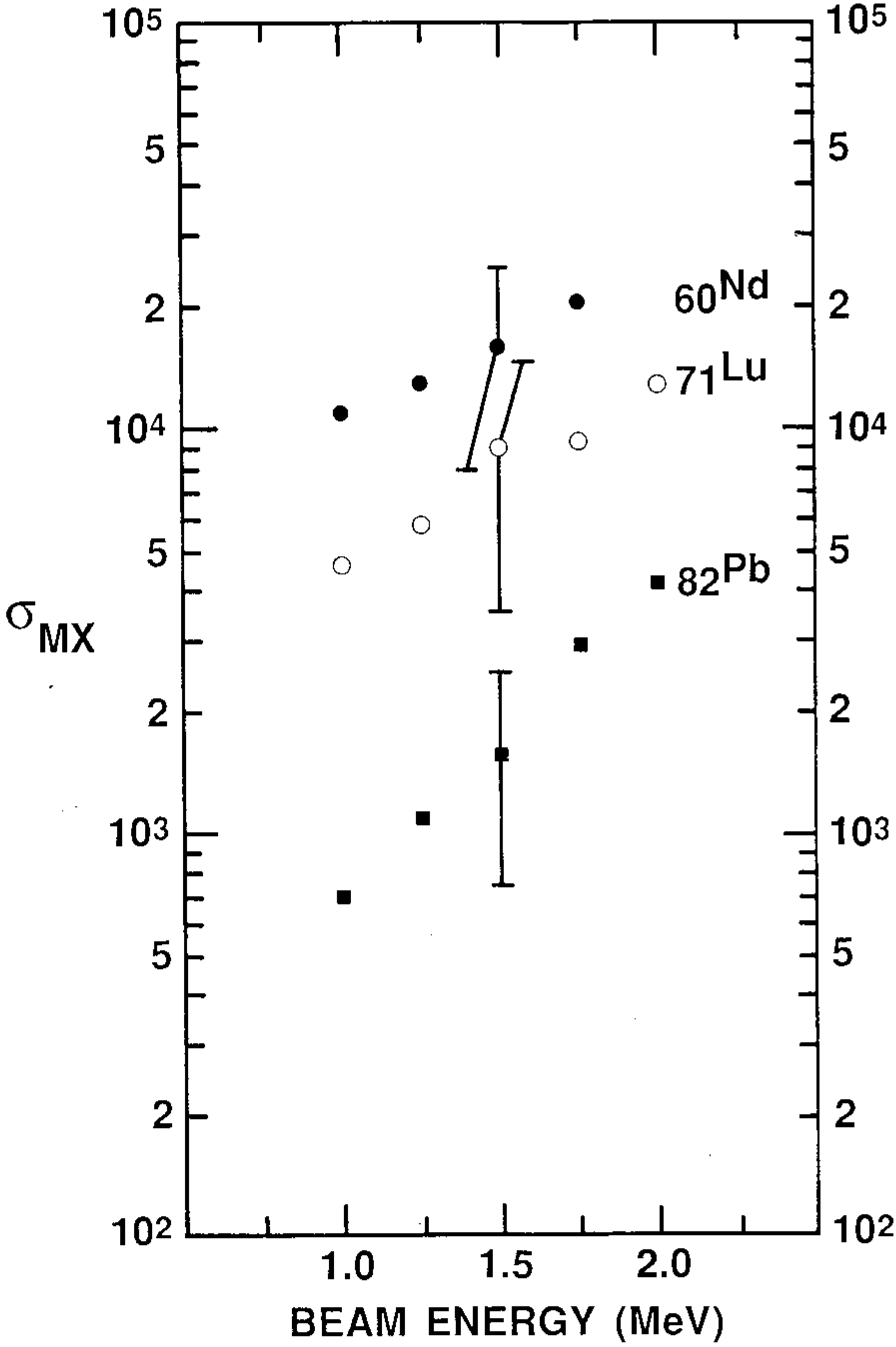
10^5
5
2
10^4
5
2
10^3
5
2
10^2
σ_{MX}
60^{Nd}
71^{Lu}
82^{Pb}
1.0
1.5
2.0
BEAM ENERGY (MeV)

Figure 36. Energy Dependence of the M-shell X-ray Production Cross Section for Ar^+ Ions Incident upon Gadolinium, Hafnium, and Uranium Targets

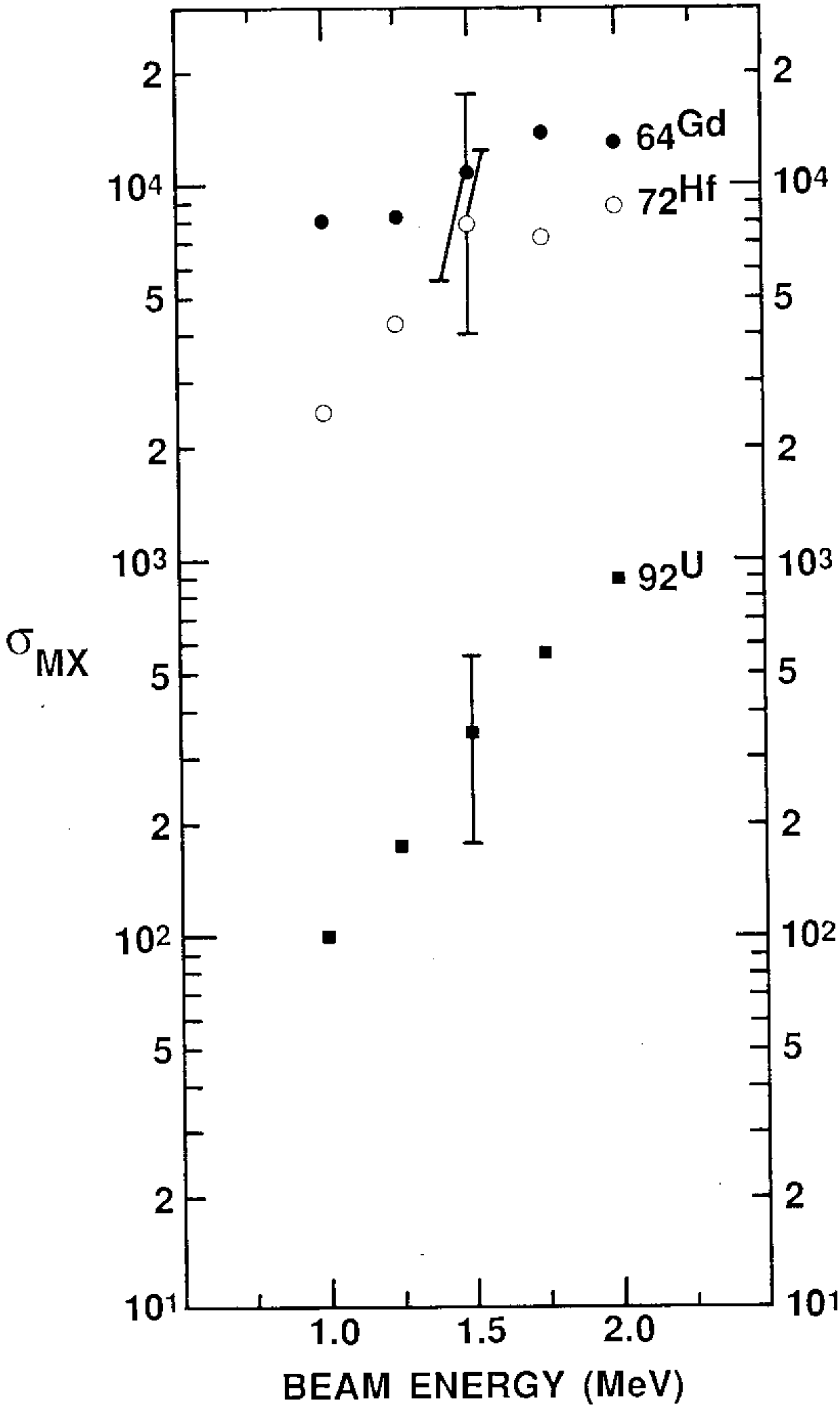
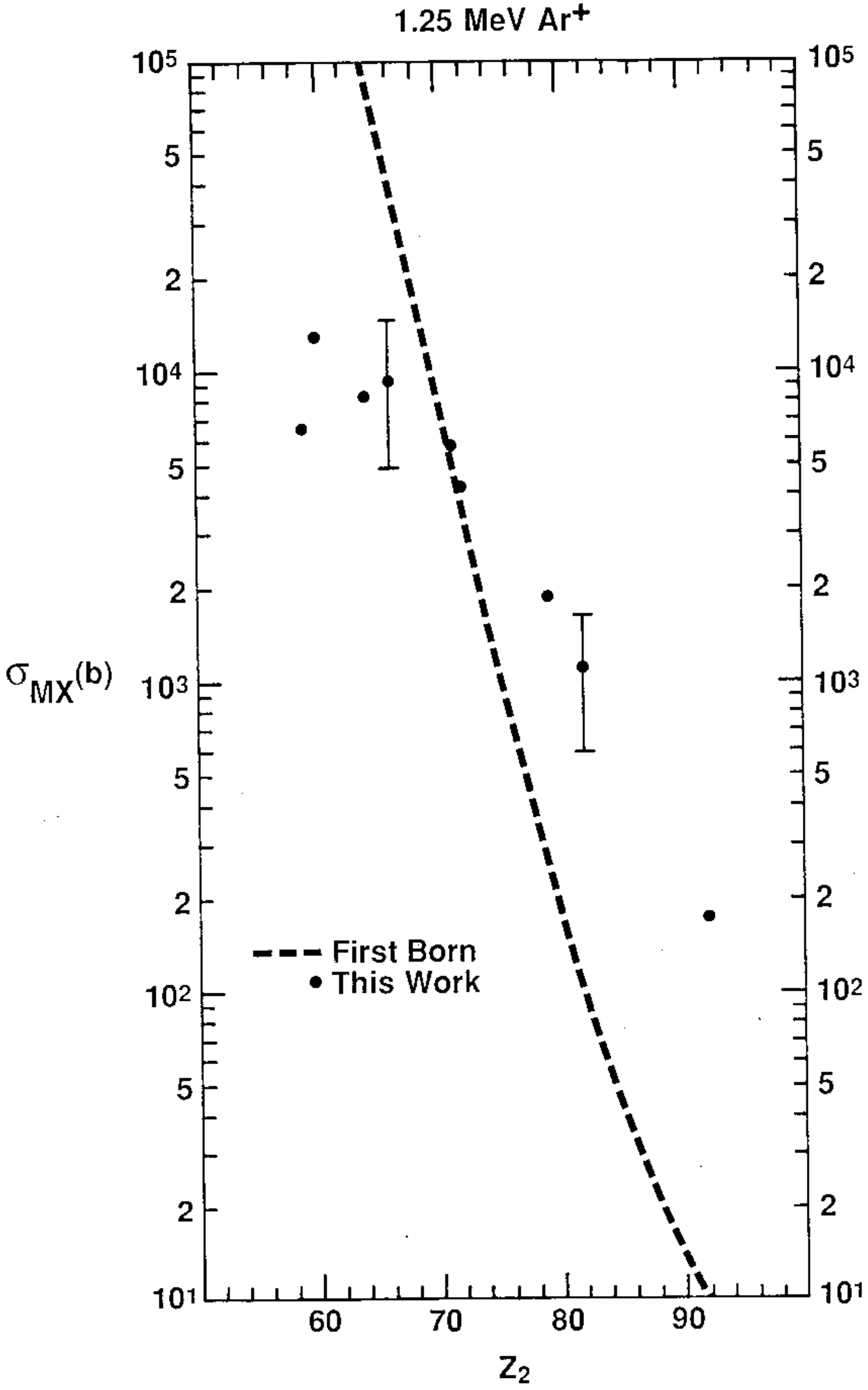

2
10^4
5
2
10^3
5
2
10^2
5
2
10^1
σ_{MX}
64Gd
72Hf
92U
1.0
1.5
2.0
BEAM ENERGY (MeV)

Figure 37. Target Atomic Number Dependence of the M-shell X-ray Production Cross Section for Ar^+ Ions



1.25 MeV Ar$^+$
σ_{MX}(b)
10^5
5
2
10^4
5
2
10^3
5
2
10^2
5
2
10^1
60
70
80
90
Z_2
First Born
This Work

that this factor overestimates the reduction in the cross section due to the trajectory deflection of the incident ions.

ANALYSIS AND CONCLUSION

It is clear that for larger incident ions (i.e. slower projectile velocities) there is an ever increasing discrepancy between the measured results and theoretical predictions. The small discrepancy with $^{9}Be^{+}$ ions can be attributed to the fluorescence yield change due to multiple ionizations of the outer electron shells of the target. Recently G. Lapicki <u>et.</u> <u>al</u>.[40] have proposed that this effect can be quantified for very light ions by a semi-empirical formula

$$\omega_s = \omega_s^{\circ}\left[1 - \frac{Z_1^2}{2\beta V_1^2}\left[1 - \frac{\beta}{4V_1^2}\left(1 - \omega_s^{\circ}\right)\right]\right] \qquad \text{(V-1)}$$

where ω_s is the net fluorescence yield including multiple ionziation effects, ω_s° is the single hole fluorescence yield, and β is an adjustable parameter. This does explain some discrepancies for $^{1}H^{+}$ and $^{4}He^{+}$ ions but for higher Z_1 there are some specific restrictions limiting the correction to higher velocities.[40] The correction factor to ω_s° was derived assuming that the outer shell electrons could be approximated as a single "collective state." Then assuming high projectile velocities and some "remnants" of J. J. Thomson's[79] "plum-cake" theory for atomic structure, the above equation was derived. The high projectile velocity dependence comes from Thomson's assumption of zero net target electron velocity. The effect of the above correction would be to cause an increase in the theory predictions for slower incident ions and could thus account for some of the discrepancy in the $^{9}Be^{+}$ results.

For the $^{27}Al^{+}$ and $^{40}Ar^{+}$ measurements, the discrepancy cannot be entirely accounted for by the fluorescence yields change. While a significant portion of the difference may be due to this effect, most of the discrepancy could probably be attributed to problems with the Coulomb deflection correction factor or the calculation of the electron capture contribution. This seems obvious since the theoretical predictions without the corrections (PWBA plus OBKN) are orders of magnitude different than that with the corrections (ECPSSR) and that the total ionization cross sections predicted by the ECPSSR theory are less than the measured x-ray production cross sections.

Further work is necessary to understand the processes involved at low velocity ion-atom collisions. More fluorescence yield measurements need to be made (preferably with gas targets) to see if equation V-1 is a sufficient generalized form to correct the single hole to the highly ionized outer shell fluorescence yields. To investigate the Coulomb deflection factor, further measurements need to be taken where the ratios of the cross sections for two identical Z_1 ions but different atomic masses are examined. All corrections due to energy loss, perturbed wavefunctions, and relativistic factors are nearly the same while the Coulomb deflection factor should be the only difference in the data. Examining these ratios would give some insight into the behavior of this factor. Good candidates for this investigation would be ^{10}B and ^{11}B, ^{12}C and ^{13}C, and ^{16}O, ^{17}O, and ^{18}O on very thin solid or gas targets.

One other possible source for the large cross section measurements as compared to the ECPSSR theory is that the Electron Capture contribution may actually be larger than that predicted by the theory. The EC contribution should be large at low velocities but the theory may still be underpredicting the actual amount. This possibility must be seriously examined since it is observed that numerous K-shell vacancies are generated in the incident aluminum and argon ions (for example, see Figure 16). Large numbers of K-shell vacancies in the projectiles will enhance electron capture (see references 25, 46, 80, 81, and 82) and then contribute greatly to the total ionization of the target. It may be necessary to abandon a Born approximation technique used for the OBKN calculation with associated corrections and adopt a different theoretical approach to explain electron capture for such low velocities as used in this work. It would be interesting to see the prediction of the Molecular Orbital theory for this velocity range and compare to the data and the ECPSSR predictions.

SUMMARY

Overall, the ECPSSR theory does adequately predict the behavior of the ion-atom cross sections for low energy (0.5 to 2.5 MeV) $^{9}Be^{+}$ ions for the K-, L-, and M-shell x-rays whose energies lie between 0.65 and 3.5 keV. Any deviations from the measurements may be due to multiple ionization effects or projectile charge state uncertainties. The ECPSSR theory currently breaks down at higher Z_1 ions ($^{27}_{13}Al^{+}$ and $^{40}_{18}Ar^{+}$). This is most likely due to inaccuracies in the Coulomb deflection correction factor with some contribution to the error from the multiple ionization effects of the target atom. There may also be an unaccounted for enhancement of the electron capture process.

APPENDIX A

Theoretical K-shell ionization and x-ray production cross sections for incident ${}^{9}_{4}Be^{+}$ ions upon F, Na, Al, Si, P, Cl, and K.

K - shell cross sections (barns)

```
N= 1      M= 2       DEFLECTION = 0.875
Z1 = 4   Z2 = 9      A1 = 9   A2 = 19     F.YIELD = 0.013
                          BINDING ENERGY = 685.87220123 (EV)      THETA = 0.606

E1(MEV)      DIRECT IONIZATION   ELECTRON CAPTURE    DI+EC        XRAY PRODUCTION
 0.25            4321.1252803     1625.5394739     5946.6647542     77.306641864   FBORN
.12164750958     6.1964093824     .54439055482     6.7407999372     .08763039918   ECPSSR

 0.5             33883.356892     17523.358770     51406.715662     668.2873036
.17203555788     291.28289504     26.388377162     317.67127220     4.1297265386

 0.75            94766.072212     61347.774579     156113.84679     2029.4800083
.21069966721     2773.4251399     243.94474815     3017.3698880     39.225808544

 1               179465.01307     137119.54677     316584.55984     4115.5992779
.24329501916     13114.994687     1119.7536305     14234.748318     185.05172813

 1.25            280195.83436     241407.36268     521603.19704     6780.8415615
.27201210071     40405.989165     3440.2677877     43846.256952     570.00134038

 1.5             390051.46889     367221.68062     757273.14951     9844.5509436
.29797432695     93151.606714     8135.9166688     101287.52336     1316.7378040

 1.75            502315.58585     506720.10683     1009035.6927     13117.464005
.32164905796     176555.11551     16019.599947     192574.71545     2503.4713009

 2               615600.75479     652660.11019     1268260.8650     16487.391245
.34407111575     288624.47612     27579.828758     316204.30488     4110.6559635

 2.25            727335.80251     799016.617       1526352.4195     19842.581454
.36494252874     424214.55002     42897.521226     467112.07124     6072.456926

 2.5             835956.06131     941128.43007     1777084.4914     23102.098388
.38468320196     579560.82552     61677.644586     641238.47011     8336.1001115

 2.75            940575.96603     1075611.1963     2016187.1623     26210.433110
.40345914596     746866.63163     83348.727987     830215.35961     10792.799675

 3               1040542.0912     1200173.1928     2240715.284      29129.298692
.42139933441     918671.75956     107182.04008     1025853.7997     13336.099395
```

```
C= 1     L= 2      IFRACTION = 0.075
Z1 = 4   Z2 = 11      A1 = 9   A2 = 23     F.YIELD = 0.023
                   BINDING ENERGY = 1072.1470005 (EV)        THETA =
 0.658266
E1(MEV)     DIRECT IONIZATION  ELECTRON CAPTURE     DI+EC      XRAY PRODUCTION

 0.25            370.57603306     48.779842155    419.35587522    9.6449781304
.09890965732     .60815880425     .02652120148    .63468000573    .01459760105

 0.5             3615.1491910     614.73586014    4229.8850511    97.287356175
.13987937883     25.515525277     1.1637807076    26.679305985    .41362403705

 0.75            11864.250142     2475.1218936    14339.372035    329.80555681
.17131655184     206.20050490     9.602432187     215.80293708    4.9680675529

 1               27476.414668     4275.7449328    31752.159600    730.2996758
.19781931464     900.48523385     43.609623609    944.09485747    21.714181722
 1.25            45787.810816     12390.070962    58177.881777    1292.0912809
.22116871740     2766.8197735     135.72517881    2902.5449523    66.758533902

 1.5             66035.604294     20928.863691    86964.467986    2000.1627637
.24227819107     6717.3700342     334.58736146    7051.9573957    162.19502010

 1.75            91245.361157     31799.114126    123044.47528    2830.0229315
.26169035554     13727.969234     699.16398308    14427.133217    331.82406400

 2               118588.01066     44769.015466    163357.02613    3757.2300010
.27975875767     24682.458187     1291.2985491    25973.756736    597.39640492

 2.25            147372.25276     59528.769055    206901.02181    4758.7235016
.29672897196     40006.486722     2167.5406840    42174.027406    970.00263032

 2.5             176874.86577     75726.251985    252601.11776    5809.8257083
.31277979972     60109.725566     3372.4191855    63482.144752    1460.0893293

 2.75            206752.42363     93006.108442    299758.53207    6894.4462376
.32804622148     84716.351255     4934.2176419    89650.568897    2061.9630846

 3               237262.80753     111026.43437    348289.24190    8010.6525636
.34263310368     113468.58962     6863.4325403    120332.02216    2767.6365097
```

```
N= 1     M= 2      FRACTION = 0.675
Z1 = 4   Z2 = 13     A1 = 9  A2 = 26.98   K-YIELD = 0.039      THETA =
                       BINDING ENERGY = 1559.6680223 (EV)
 0.710713
E1(MEV)     DIRECT IONIZATION  ELECRON CAPTURE    DI+EC     XRAY PRODUCTION
                                                  45.462525872   1.7730385090
 0.25          42.973405169    2.5691207033      .07968523587   .00310772420
 .08333333333  .07771653083    .00196670503
                                                  518.30145356   20.213756690
 0.5           462.85865965    35.442703925      3.7266091161   .14534555553
 .11785113020  3.6335879217    .09322119437
                                                  1930.5562304   79.201602986
 0.75          1776.4234218    154.13280464      28.205419074   1.1000113459
 .14433756730  27.464005530    .74141354444
                                                  4613.7709127   179.93706560
 1             4193.7246857    420.04622698      114.92367673   4.4820312794
 .16666666667  111.77750319    3.1483755362
                                                  8695.6556076   339.13097162
 1.25          7808.2205509    667.43513464      337.22333307   13.151710103
 .18633899813  327.68172691    9.5416090588
                                                  14185.482906   353.23384336
 1.5           12567.658923    1597.8239826      803.57102023   31.339270025
 .20412414523  760.22143673    23.349589543
                                                  21011.641572   819.45402129
 1.75          16433.102401    2578.5301710      1650.1840401   64.357177503
 .22047927592  1601.0417873    49.142252766
                                                  28956.232053   1129.2930600
 2             25112.809032    3843.4230202      3030.0758450   118.17295795
 .23570226040  2937.6595475    92.416297412
                                                  38105.214626   1406.1033762
 2.25          32710.626633    5394.5879923      5095.0157261   196.70561332
 0.25          4935.7821491    159.23357693
                                                  48157.367719   1876.1373410
 2.5           40932.815889    7224.5518291      7987.4320879   311.50985143
 .26352313835  7731.6371094    255.79497844
                                                  58936.114605   2298.5084696
 2.75          49617.726137    9318.3884684      11814.308632   460.75803604
 .27638539920  11426.294010    388.01462238
                                                  70450.94613    2747.5868971
 3             58795.239752    11655.706378      16643.894052   649.11189921
 .28867513460  16082.747910    561.14694148
```

```
Q= 1     N= 2     LFRACTION = 0.675
Z1 = 4   Z2 = 14     A1 = 9   A2 = 28.09     F.YIELD = 0.05          THETA =
                       BINDING ENERGY = 1838.9802997 (EV)
 0.720121
E1(MEV)       DIRECT IONIZATION  ELECTRON CAPTURE     DI+EC      XRAY PRODUCTION
 0.25              16.320674325    .71675166674     17.037425992    .65187129957
.07725060827       .02908795476    5.83340374-4     .02967129515    .00148356476
 0.5               193.40286372    10.073478046     203.47634176    10.173817068
.10924885792       1.5388870507    .03072684231     1.5696158930    .07848079465
 0.75              743.09217972    44.919311349     788.01149108    39.400574550
.13380197845       11.603431853    .24307385000     11.846505703    .59232526917
 1                 1618.6826216    125.37664176     1944.0592634    97.202963169
.15450121655       46.418965905    1.0153801426     47.434346048    2.3717173924
 1.25              3495.9348581    271.00149252     3766.9363506    186.34661753
.17273761140       133.73589950    3.0390511596     136.77495065    6.8387475327
 1.5               5795.5261642    498.71030415     6294.2364684    314.71182342
.18922457259       313.64873422    7.3759185248     321.02375274    16.051187637
 1.75              8695.2352449    821.62173245     9517.0569773    475.85284087
.20438589812       640.0509052     15.463444670     655.51434986    32.775717494
 2                 12148.708205    1249.7838735     13398.492079    669.92460392
.21849771584       1172.0044922    29.085838865     1201.0903310    60.054516551
 2.25              16069.666523    1788.3055176     17857.972041    892.89860204
.23175182482       1976.4991424    50.287222909     2026.7863653    101.33931827
 2.5               20447.44917     2439.7090330     22887.158203    1144.3579102
.24428787278       3117.0499959    61.271349113     3178.3213450    159.91606725
 2.75              25213.907009    3203.3885055     28417.295505    1420.8647753
.25621126247       4648.2071785    124.28348973     4772.4908682    238.62454341
 3                 30346.274720    4076.3006421     34422.575362    1721.1287681
.26760595669       6627.1640604    181.49578650     6808.6598069    340.43299535
```

```
N= 1     M= 2     LFRACTION = 0.675
Z1 = 4   Z2 = 15     A1 = 9   A2 = 30.97     F YIELD = 0.063      THETA =
                     BINDING ENERGY = 2145.5941259 (EV)
 0.729764
E1(MEV)      DIRECT IONIZATION  ELECTRON CAPTURE     DI+EC       XRAY PRODUCTION
 0.25           6.6023243071      .21529242182     6.8176167285    .02950985392
.07199546455     .01125378181    1.21388170-4      .01143516795   7.304157?9-4
 0.5            89.88920792      3.0880430424     83.978250964    5.2906298197
.10181696252     .08670185006     .01034349583     .69754534589    .04394535679
 0.75          322.00316233     14.050861881     336.05902421     21.171715525
.12469980304    5.2254365169      .0061351?973     5.3115717180    .33462901827

 1             813.34404627     39.973911809     853.31775803     53.759031359
.14399092971    20.666491804      .35574614330     21.022237947    1.3244009907

 1.25          1607.5098866     88.005206175     1695.5150928     106.81785085
.16098675348    55.743253216     1.0522582102     59.795511427    3.7671172199

 1.5           2730.5504715     164.84205940     2895.3925509     182.40973071
.17635215269    136.33282716     2.5305771022     138.86340425    8.7483944684

 1.75          4187.0231842     276.31519862     4463.3383828     281.19031812
.19048209553    275.20875953     5.2755099011     280.48426943    17.670508974

 2             5968.4300348     427.17966415     6395.6596989     402.92656104
.20363392565    502.36174843     9.896518414     512.25826685    32.272270812

 2.25          6054.5626004     621.04365806     8675.6062584     546.56319428
.21598639456    845.68146792     17.110774854     862.79224277    54.355911295

 2.5           10423.005874     860.38625956     11283.392134     710.65370442
.22766965014    1337.1666935     27.717070505     1364.8837640    85.967677131

 2.75          13001.637659     1146.6297686     14148.267428     891.34084796
.23878194352    2003.4454002     42.563847191     2046.5092474    128.93008259

 3             15866.304244     1480.2439395     17346.547284     1092.8324789
.24939960608    2874.3816274     62.51472579     2936.0963532    185.02847925
```

```
Q= 1     N= 2     FRACTION = 0.075

Z1 = 4  Z2 = 17     A1 = 9  A2 = 35.45     F.YIELD = 0.097
                    BINDING ENERGY = 2822.5242571 (EV)        THETA =
 0.743831

E1(MEV)      DIRECT IONIZATION  ELECTRON CAPTURE    DI+EC      XRAY PRODUCTION

 0.25          1.2832892373     .0257365346      1.3090257719     .12697549997
.06337325349   .00173700999     1.89127616-5     .00175592275     1.70324507-4

 0.5           16.812395410     .37994171734     17.192337127     1.6676567014
.08962351458   .15634107514     .00161982839     .15796090354     .01532220764

 0.75          70.597414305     1.7765608272     72.373975132     7.0202755878
.10976569489   1.2664870432     .01350659611     1.2799936393     .12415938301

 1             167.21750682     5.1912364236     172.40874324     16.723648094
.12674650699   5.0047275709     .05569435451     5.0604219254     .49086092676
 1.25          386.59767744     11.729285531     398.32696297     38.637715408
.14170690277   14.069138927     .16271840557     14.231857332     1.3804901612

 1.5           632.3660946      22.530453958     654.89654856     63.524965211
.15523213440   32.204285975     .38628129816     32.590567273     3.1612850255

 1.75          1084.6223369     38.701882597     1123.3242195     108.96244929
.16766986852   64.250506953     .79683960984     65.047346563     6.3095926166

 2             1596.1830645     61.272220409     1657.4552849     160.77316264
.17924662917   116.10786997     1.4839795620     117.59184954     11.406409405

 2.25          2219.8471198     91.162705452     2311.0098253     224.16795305
.19011976048   194.04477549     2.5555935799     196.60036907     19.070235800

 2.5           2951.0814839     129.16939917     3080.2508830     298.78433565
.20040382377   305.94143546     4.1359838834     310.07741934     30.077509676

 2.75          3789.6398026     175.95517128     3965.5949739     384.66271247
.21018530358   459.07466948     6.3630951577     465.43776464     45.14746317

 3             4725.3559801     232.04794656     4957.4039267     480.86818089
.21953138978   661.56012977     9.3851187946     670.94524857     65.081689112
```

```
Q= 1      N= 2      LFRACTION = 0.675
Z1 = 4   Z2 = 19      A1 = 9   A2 = 39.1      K.YIELD = 0.14
                        BINDING ENERGY = 3607.5594502 (EV)         THETA =
 0.758224
E1(MEV)       DIRECT IONIZATION  ELECTRON CAPTURE    DI+EC      XRAY PRODUCTION
 0.25             .29113617282     .00384040459     .29497657741     .04129672064
.05659530542     2.53135737-4     1.92657558-6     2.55062315-4     3.57087258-5
 0.5              5.9906862414     .05779502613     6.0484812676     .56678737746
.08005793354     .03627277901     2.70526801-4     .03654330581     .00539600201
 0.75             17.471603765     .27536331070     17.746967076     2.4845753906
.09802604838     .34378164098     .00247681903     .34625846001     .04847610446
 1                47.933293655     .81952660784     48.752820263     6.0253946567
.11319073064     1.3978488346     .01043990277     1.4082887374     .19716042323
 1.25             102.43837403     1.8851709371     104.32354497     14.605296295
.12655100429     3.9427834456     .03054312083     3.9733265664     .55626571930
 1.5              166.35175956     3.6852239091     170.03698353     24.605177695
.13862976708     8.9992777470     .07213429425     9.0714120440     1.2699976862
 1.75             304.67420650     6.4398308268     311.11403735     43.555963226
.14973720226     17.835172650     .14781180156     17.982984457     2.5176178240
 2                460.56221277     10.368021953     470.93023462     65.930232847
.16007580669     31.976610054     .27356860375     32.250178657     4.5150250120
 2.25             656.2796695      15.681407875     671.96107737     90.074550832
.16978609624     53.274425848     .46878997909     53.743215827     7.5240502157
 2.5              892.4761412      22.579524299     915.0556655      128.10779317
.17897025973     83.701551832     .75611224027     84.457664072     11.824072970
 2.75             1170.0634566     31.246508096     1201.3099647     168.18339506
.18770559197     125.21894577     1.1611578136     126.38010358     17.693214501
 3                1488.7150377     41.848847088     1530.5638848     214.27894307
.19605209676     180.40986082     1.7121671881     182.12202801     25.497083921
```

APPENDIX B

Theoretical L-shell ionization and x-ray production cross sections for incident $^{9}_{4}Be^{+}$ ions upon Cu, Zn, Ge, Br, Zr, Mo, and Ag.

$_{29}$Cu

```
*JUNE 1985                                                                                          O. LAPICKI.. EAST CAROLINA UNIVERSITY
==============================================================================================================================
Z1=  4    Z2= 29                                           ****  L-SHELL CROSS SECTIONS (BARN) ****
FLUORESCENCE & COSTER-KRONIG YIELDS FROM KRAUSE (1979)
                                          FIRST BORN APPROXIMATION                                              ECPSSR THEORY
                        -----------------------------------------------------------        ------------------------------------------------------
E1(MEV) E1(MEV)/A1(U)   DIRECT + CAPTURE = IONIZATION XRAY PROD.   C/I              DIRECT + CAPTURE = IONIZATION XRAY-PROD.   C/I
--------------------------------------------------------------------------------------------------------------------------------------------------

 0.250      0.028      6.36D+03  7.74D+02  7.13D+03  7.67D+01  0.1085          3.82D+01  1.47D+00  3.97D+01  4.25D-01  0.0371
 0.500      0.056      4.29D+04  1.12D+04  5.41D+04  5.83D+02  0.2069          1.26D+03  6.71D+01  1.34D+03  1.44D+01  0.0499
 0.750      0.083      1.09D+05  4.44D+04  1.54D+05  1.66D+03  0.2892          7.01D+03  5.25D+02  7.53D+03  8.11D+01  0.0695
 1.000      0.111      2.00D+05  1.05D+05  3.05D+05  3.29D+03  0.3443          2.10D+04  2.17D+03  2.32D+04  2.50D+02  0.0935
 1.250      0.139      3.11D+05  1.89D+05  5.01D+05  5.43D+03  0.3770          4.63D+04  6.20D+03  5.25D+04  5.66D+02  0.1181
 1.500      0.167      4.39D+05  2.89D+05  7.29D+05  7.85D+03  0.3970          8.46D+04  1.38D+04  9.84D+04  1.06D+03  0.1399
 1.750      0.194      5.80D+05  3.97D+05  9.77D+05  1.05D+04  0.4065          1.37D+05  2.55D+04  1.63D+05  1.75D+03  0.1571
 2.000      0.222      7.29D+05  5.06D+05  1.23D+06  1.33D+04  0.4097          2.04D+05  4.16D+04  2.46D+05  2.65D+03  0.1693
 2.250      0.250      8.83D+05  6.12D+05  1.49D+06  1.61D+04  0.4093          2.85D+05  6.13D+04  3.47D+05  3.74D+03  0.1770
 2.500      0.278      1.04D+06  7.11D+05  1.75D+06  1.88D+04  0.4061          3.80D+05  8.38D+04  4.64D+05  5.00D+03  0.1808
 2.750      0.306      1.20D+06  8.01D+05  2.00D+06  2.15D+04  0.4012          4.86D+05  1.08D+05  5.94D+05  6.40D+03  0.1812
 3.000      0.333      1.35D+06  8.93D+05  2.24D+06  2.41D+04  0.3951          6.03D+05  1.31D+05  7.34D+05  7.91D+03  0.1789


J. A. BEARDEN AND A. F. BURR, REV. MOD. PHYS. 39, 125 (1967):
OBSERVED BINDING ENERGIES (EV): BL1= 1096.6  BL2=  951.0  BL3=  931.1
THETA =4*BL(EV)/Z2L/13.605(EV): TL1= 0.9221  TL2= 0.4528  TL3= 0.4833

W. BAMBYNEK ET AL., REV. MOD. PHYS. 44, 716 (1972):
                                              W1           W2           W3
SUBSHELL FLUORESCENCE YIELDS              0.0003       0.0060       0.0094
                                             F12          F23          F13
COSTER-KRONIG  PROBABILITIES               0.328        0.805        0.623

M. O. KRAUSE, J. PHYS. CHEM. REF. DATA 8, 307 (1979):
                                              W1           W2           W3
SUBSHELL FLUORESCENCE YIELDS              0.0016       0.0103       0.0115
                                             F12          F23          F13
COSTER-KRONIG  PROBABILITIES               0.300        0.028        0.540

UNOCCUPIED K,L,M,N FRACTIONS FOR  G =  1.00 : 0.000 0.875 1.000 1.000
```

Zn
30

```
*JUNE  1985                                                                                            G. LAPICKI   EAST CAROLINA UNIVERSITY
=========================================================================================================================================

Z1=  4    Z2= 30                                            ****  L-SHELL CROSS SECTIONS (BARN) ****
 FLUORESCENCE & COSTER-KRONIG YIELDS FROM KRAUSE [1979]
                                            FIRST BORN APPROXIMATION                                                     ECPSSR-THEORY
                            ---------------------------------------------------------------    ---------------------------------------------------------------
 E1(MEV) E1(MEV)/A1(U)  DIRECT + CAPTURE = IONIZATION XRAY PROD.   C/I          DIRECT + CAPTURE = IONIZATION XRAY PROD.   C/I
-------------------------------------------------------------------------------------------------------------------------------------------
  0.250        0.028     3.92D+03  3.67D+02  4.29D+03  5.03D+01   0.0855          2.25D+01  7.51D-01  2.32D+01  2.71D-01   0.0323
  0.500        0.056     2.81D+04  5.51D+03  3.36D+04  3.96D+02   0.1640          8.14D+02  3.59D+01  8.50D+02  9.95D+00   0.0422
  0.750        0.083     7.37D+04  2.28D+04  9.65D+04  1.14D+03   0.2366          4.51D+03  2.75D+02  4.79D+03  5.62D+01   0.0575
  1.000        0.111     1.37D+05  5.62D+04  1.93D+05  2.26D+03   0.2915          1.36D+04  1.13D+03  1.48D+04  1.74D+02   0.0763
  1.250        0.139     2.16D+05  1.05D+05  3.21D+05  3.78D+03   0.3265          3.02D+04  3.23D+03  3.35D+04  3.94D+02   0.0965
  1.500        0.167     3.08D+05  1.65D+05  4.73D+05  5.57D+03   0.3491          5.57D+04  7.28D+03  6.30D+04  7.42D+02   0.1156
  1.750        0.194     4.10D+05  2.33D+05  6.43D+05  7.57D+03   0.3623          9.09D+04  1.38D+04  1.05D+05  1.23D+03   0.1316
  2.000        0.222     5.20D+05  3.04D+05  8.25D+05  9.70D+03   0.3692          1.36D+05  2.29D+04  1.59D+05  1.87D+03   0.1441
  2.250        0.250     6.35D+05  3.76D+05  1.01D+06  1.19D+04   0.3717          1.92D+05  3.46D+04  2.26D+05  2.66D+03   0.1528
  2.500        0.278     7.54D+05  4.45D+05  1.20D+06  1.41D+04   0.3713          2.57D+05  4.84D+04  3.05D+05  3.60D+03   0.1584
  2.750        0.306     8.74D+05  5.11D+05  1.39D+06  1.63D+04   0.3689          3.31D+05  6.37D+04  3.95D+05  4.65D+03   0.1612
  3.000        0.333     9.95D+05  5.72D+05  1.57D+06  1.84D+04   0.3651          4.14D+05  7.97D+04  4.94D+05  5.81D+03   0.1614


 J. A. BEARDEN AND A. F. BURR, REV. MOD. PHYS. 39, 125 (1967):
 OBSERVED BINDING ENERGIES (EV): BL1= 1193.6  BL2= 1042.8  BL3= 1019.7
 THETA =4*BL(EV)/Z2L/13.605(EV): TL1= 0.5252  TL2= 0.4588  TL3= 0.4487

 W. BAMBYNEK ET AL., REV. MOD. PHYS. 44, 716 (1972):
                                             W1           W2           W3
 SUBSHELL FLUORESCENCE YIELDS            0.0005       0.0009       0.0108
                                            F12          F23          F13
 COSTER-KRONIG  PROBABILITIES             0.322        0.000        0.624

 M. O. KRAUSE, J. PHYS. CHEM. REF. DATA 8, 307 (1979):
                                             W1           W2           W3
 SUBSHELL FLUORESCENCE YIELDS            0.0019       0.0113       0.0126
                                            F12          F23          F13
 COSTER-KRONIG  PROBABILITIES             0.290        0.026        0.540

 UNOCCUPIED (K,L,M) FRACTIONS FOR  Q =  1.00 : 0.000 0.375 1.000 1.000
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Ge
32

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*JUNE 1985                                                                                     G. LAPICKI, EAST CAROLINA UNIVERSITY
=====================================================================================================================================

Z1= 4    Z2= 32                                     **** L-SHELL CROSS SECTIONS (BARN) ****

FLUORESCENCE & COSTER-KRONIG YIELDS FROM KRAUSE (1979)
                                        FIRST BORN APPROXIMATION                                          ECPSSR THEORY
                         ---------------------------------------------------------  ---------------------------------------------------------
E1(MEV) E1(MEV)/A1(U)    DIRECT + CAPTURE = IONIZATION XRAY PROD.   C/I          DIRECT + CAPTURE = IONIZATION XRAY PROD.   C/I
-------------------------------------------------------------------------------------------------------------------------------------
  0.250      0.028       1.46D+03  8.43D+01  1.56D+03  2.26D+01  0.0541        7.50D+00  1.91D-01  7.70D+00  1.10D-01  0.0248
  0.500      0.056       1.20D+04  1.35D+03  1.33D+04  1.94D+02  0.1016        3.33D+02  1.05D+01  3.44D+02  4.97D+00  0.0305
  0.750      0.083       3.34D+04  6.03D+03  3.94D+04  5.75D+02  0.1528        1.91D+03  7.93D+01  1.99D+03  2.89D+01  0.0399
  1.000      0.111       6.84D+04  1.59D+04  8.43D+04  1.17D+03  0.1889        5.85D+03  3.18D+02  6.17D+03  8.99D+01  0.0515
  1.250      0.139       1.04D+05  3.16D+04  1.35D+05  1.96D+03  0.2331        1.32D+04  9.08D+02  1.41D+04  2.05D+02  0.0645
  1.500      0.167       1.51D+05  5.27D+04  2.04D+05  2.97D+03  0.2569        2.46D+04  2.08D+03  2.66D+04  3.89D+02  0.0780
  1.750      0.194       2.04D+05  7.84D+04  2.83D+05  4.13D+03  0.2770        4.05D+04  4.04D+03  4.46D+04  6.51D+02  0.0906
  2.000      0.222       2.64D+05  1.07D+05  3.71D+05  5.41D+03  0.2882        6.15D+04  6.96D+03  6.84D+04  9.99D+02  0.1017
  2.250      0.250       3.27D+05  1.36D+05  4.65D+05  6.78D+03  0.2920        8.75D+04  1.09D+04  9.83D+04  1.44D+03  0.1107
  2.500      0.278       3.94D+05  1.70D+05  5.64D+05  8.22D+03  0.3015        1.19D+05  1.58D+04  1.34D+05  1.96D+03  0.1176
  2.750      0.306       4.63D+05  2.02D+05  6.65D+05  9.69D+03  0.3035        1.55D+05  2.16D+04  1.76D+05  2.57D+03  0.1227
  3.000      0.333       5.34D+05  2.33D+05  7.67D+05  1.12D+04  0.3039        1.96D+05  2.82D+04  2.24D+05  3.27D+03  0.1260


J. A. BEARDEN AND A. F. BURR, REV. MOD. PHYS. 39, 125 (1967):
OBSERVED BINDING ENERGIES (EV): BL1= 1414.3  BL2= 1247.8  BL3= 1216.7
THETA =4*BL(EV)/Z2L/(13.605(EV): TL1= 0.5361  TL2= 0.4730  TL3= 0.4612

W. BAMBYNEK ET AL., REV. MOD. PHYS. 44, 716 (1972):
                                                       W1           W2           W3
SUBSHELL FLUORESCENCE YIELDS                        0.0000       0.0000       0.0144
                                                       F12          F23          F13
COSTER-KRONIG  PROBABILITIES                         0.266        0.005        0.471

M. O. KRAUSE, J. PHYS. CHEM. REF. DATA 8, 307 (1979):
                                                       W1           W2           W3
SUBSHELL FLUORESCENCE YIELDS                        0.0024       0.0130       0.0150
                                                       F12          F23          F13
COSTER-KRONIG  PROBABILITIES                         0.280        0.056        0.530

UNOCCUPIED K,L,M,N FRACTIONS FOR  Q =  1.00 : 0.000 0.075 1.000 1.000
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35Br

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*JUNE 1985                                                                                                     G. LAPICKI, EAST CAROLINA UNIVERSITY
==================================================================================================================================================

Z1=  4     Z2= 35                                   **** L-SHELL CROSS SECTIONS (BARN) ****
FLUORESCENCE & COSTER-KRONIG YIELDS FROM KRAUSE (1979)
                                     FIRST BORN APPROXIMATION                                                      ECPSSR THEORY
                      ---------------------------------------------------------            ----------------------------------------------------------
E1(MEV) E1(MEV)/A1(U)  DIRECT + CAPTURE = IONIZATION XRAY PROD.    C/I               DIRECT + CAPTURE = IONIZATION XRAY PROD.    C/I
-------------------------------------------------------------------------------------------------------------------------------------------------
 0.250     0.028       3.72D+02  1.16D+01  3.83D+02  7.59D+00  0.0301             1.43D+00  2.56D-02  1.46D+00  2.86D-02  0.0176
 0.500     0.056       3.51D+03  1.94D+02  3.70D+03  7.35D+01  0.0525             9.39D+01  1.92D+00  9.58D+01  1.89D+00  0.0200
 0.750     0.083       1.08D+04  9.31D+02  1.17D+04  2.33D+02  0.0796             5.82D+02  1.48D+01  5.97D+02  1.13D+01  0.0248
 1.000     0.111       2.20D+04  2.64D+03  2.46D+04  4.90D+02  0.1074             1.83D+03  5.61D+01  1.89D+03  3.75D+01  0.0297
 1.250     0.139       3.67D+04  5.69D+03  4.24D+04  8.43D+02  0.1352             4.19D+03  1.64D+02  4.36D+03  8.66D+01  0.0376
 1.500     0.167       5.47D+04  1.01D+04  6.48D+04  1.29D+03  0.1554             7.95D+03  3.74D+02  8.33D+03  1.66D+02  0.0450
 1.750     0.194       7.59D+04  1.59D+04  9.18D+04  1.83D+03  0.1735             1.33D+04  7.39D+02  1.41D+04  2.80D+02  0.0525
 2.000     0.222       9.97D+04  2.31D+04  1.23D+05  2.44D+03  0.1881             2.05D+04  1.31D+03  2.18D+04  4.34D+02  0.0599
 2.250     0.250       1.25D+05  3.14D+04  1.57D+05  3.13D+03  0.1993             2.95D+04  2.11D+03  3.16D+04  6.30D+02  0.0668
 2.500     0.278       1.55D+05  4.05D+04  1.95D+05  3.88D+03  0.2078             4.05D+04  3.18D+03  4.37D+04  8.70D+02  0.0729
 2.750     0.306       1.85D+05  5.02D+04  2.35D+05  4.68D+03  0.2141             5.35D+04  4.53D+03  5.81D+04  1.16D+03  0.0780
 3.000     0.333       2.17D+05  6.05D+04  2.77D+05  5.52D+03  0.2186             6.85D+04  6.14D+03  7.47D+04  1.49D+03  0.0823


J. A. BEARDEN AND A. F. BURR, REV. MOD. PHYS. 39, 125 (1967):
OBSERVED BINDING ENERGIES (EV): BL1= 1782.0  BL2= 1596.0  BL3= 1549.9
THETA =4*BL(EV)/Z2L/13.605(EV): TL1= 0.5505  TL2= 0.4930  TL3= 0.4788

W. BAMBYNEK ET AL., REV. MOD. PHYS. 44, 716 (1972):
SUBSHELL FLUORESCENCE YIELDS                  W1          W2          W3
                                          0.0015      0.0006      0.0207
COSTER-KRONIG  PROBABILITIES                 F12         F23         F13
                                           0.264       0.000       0.651

M. O. KRAUSE, J. PHYS. CHEM. REF. DATA 8, 307 (1979):
SUBSHELL FLUORESCENCE YIELDS                  W1          W2          W3
                                          0.0036      0.0159      0.0203
COSTER-KRONIG  PROBABILITIES                 F12         F23         F13
                                           0.260       0.048       0.528

UNOCCUPIED K,L,M,N FRACTIONS FOR  Q =  1.00 ! 0.000 0.875 1.000 1.000
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*JUNE  1985                                                                                    G. LAPICKI   EAST CAROLINA UNIVERSITY
=====================================================================================================================================

Z1=  4    Z2= 40                                      ****  L-SHELL CROSS SECTIONS (BARN) ****

 FLUORESCENCE & COSTER-KRONIG YIELDS FROM KRAUSE (1979)
                                  FIRST BORN APPROXIMATION                                                  ECPSSR THEORY
                        -----------------------------------------------------------          -------------------------------------------------------
 E1(MEV) C1(MEV)/A1(U)  DIRECT + CAPTURE = IONIZATION XRAY PROD.   C/I                DIRECT + CAPTURE = IONIZATION XRAY PROD.   C/I
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  0.250      0.028      4.320+01  6.010-01  4.380+01  1.370+00   0.0137           7.490-02  8.230-04  7.550-02  2.370-03   0.0109
  0.500      0.056      4.940+02  1.040+01  5.040+02  1.580+01   0.0206           1.160+01  1.310-01  1.190+01  3.740-01   0.0110
  0.750      0.083      1.750+03  5.310+01  1.800+03  5.650+01   0.0294           9.090+01  1.160+00  9.210+01  2.850+00   0.0126
  1.000      0.111      3.950+03  1.630+02  4.110+03  1.290+02   0.0395           3.110+02  4.670+00  3.160+02  5.990+00   0.0148
  1.250      0.139      7.070+03  3.750+02  7.440+03  2.330+02   0.0504           7.430+02  1.310+01  7.560+02  2.370+01   0.0173
  1.500      0.167      1.110+04  7.220+02  1.180+04  3.690+02   0.0613           1.450+03  2.950+01  1.490+03  4.630+01   0.0200
  1.750      0.194      1.590+04  1.230+03  1.710+04  5.350+02   0.0719           2.480+03  5.850+01  2.540+03  7.960+01   0.0230
  2.000      0.222      2.150+04  1.910+03  2.340+04  7.320+02   0.0817           3.890+03  1.040+02  4.000+03  1.250+02   0.0261
  2.250      0.250      2.780+04  2.780+03  3.060+04  9.530+02   0.0907           5.710+03  1.720+02  5.880+03  1.840+02   0.0293
  2.500      0.278      3.490+04  3.820+03  3.870+04  1.210+03   0.0987           7.960+03  2.640+02  8.220+03  2.570+02   0.0321
  2.750      0.306      4.270+04  5.040+03  4.770+04  1.490+03   0.1057           1.070+04  3.910+02  1.110+04  3.460+02   0.0354
  3.000      0.333      5.100+04  6.430+03  5.750+04  1.800+03   0.1118           1.380+04  5.510+02  1.440+04  4.510+02   0.0383


 J. A. BEARDEN AND A. F. BURR, REV. MOD. PHYS. 39, 125 (1967):
 OBSERVED BINDING ENERGIES (EV): BL1= 2531.6  BL2= 2306.7  BL3= 2222.3
 THETA =4*BL(EV)/Z2L/13.605(EV): TL1= 0.9791  TL2= 0.5277  TL3= 0.5086


 W. BAMBYNEK ET AL., REV. MOD. PHYS. 44, 716 (1972):
 SUBSHELL FLUORESCENCE YIELDS                              W1            W2            W3
                                                         0.0080        0.0294        0.0295
 COSTER-KRONIG  PROBABILITIES                              F12           F23           F13
                                                         0.236         0.116         0.648

 M. O. KRAUSE, J. PHYS. CHEM. REF. DATA 8, 307 (1979):
 SUBSHELL FLUORESCENCE YIELDS                              W1            W2            W3
                                                         0.0068        0.0280        0.0310
 COSTER-KRONIG  PROBABILITIES                              F12           F23           F13
                                                         0.260         0.132         0.520

 UNOCCUPIED K,L,M,N FRACTIONS FOR  Q =  1.00 : 0.000 0.875 1.000 1.000
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42 Mo

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*JUNE  1985                                                                                    G. LAPICKI   EAST CAROLINA UNIVERSITY
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Z1=  4    Z2= 42                                        ****  L-SHELL CROSS SECTIONS (BARN) ****
 FLUORESCENCE & COSTER-KRONIG YIELDS FROM KRAUSE (1979)
                                    FIRST BORN APPROXIMATION                                                     ECPSSR THEORY
                          ------------------------------------------------------------------------------------------------------------
 E1(MEV) E1(MEV)/A1(U)   DIRECT + CAPTURE = IONIZATION XRAY PROD.   C/I          DIRECT + CAPTURE = IONIZATION XRAY PROD.   C/I
----------------------------------------------------------------------------------------------------------------------------------

  0.250       0.028      2.02D+01  2.17D-01  2.04D+01  7.54D-01   0.0106       2.25D-02  2.10D-04  2.27D-02  8.35D-04   0.0093
  0.500       0.056      2.43D+02  3.76D+00  2.47D+02  9.17D+00   0.0153       5.36D+00  4.87D-02  5.41D+00  2.00D-01   0.0090
  0.750       0.083      9.01D+02  1.95D+01  9.21D+02  3.44D+01   0.0211       4.59D+01  4.67D-01  4.64D+01  1.72D+00   0.0101
  1.000       0.111      2.11D+03  6.06D+01  2.17D+03  8.10D+01   0.0280       1.65D+02  1.92D+00  1.66D+02  6.19D+00   0.0115
  1.250       0.139      3.87D+03  1.42D+02  4.01D+03  1.50D+02   0.0355       4.02D+02  5.41D+00  4.07D+02  1.52D+01   0.0133
  1.500       0.167      6.17D+03  2.79D+02  6.45D+03  2.42D+02   0.0433       7.95D+02  1.23D+01  8.07D+02  3.01D+01   0.0152
  1.750       0.194      8.99D+03  4.85D+02  9.48D+03  3.56D+02   0.0512       1.37D+03  2.43D+01  1.40D+03  5.23D+01   0.0174
  2.000       0.222      1.23D+04  7.69D+02  1.31D+04  4.91D+02   0.0588       2.17D+03  4.33D+01  2.21D+03  8.29D+01   0.0196
  2.250       0.250      1.61D+04  1.14D+03  1.72D+04  6.47D+02   0.0660       3.20D+03  7.15D+01  3.27D+03  1.23D+02   0.0219
  2.500       0.278      2.03D+04  1.66D+03  2.19D+04  8.24D+02   0.0757       4.49D+03  1.11D+02  4.60D+03  1.73D+02   0.0242
  2.750       0.306      2.50D+04  2.14D+03  2.72D+04  1.02D+03   0.0789       6.04D+03  1.64D+02  6.20D+03  2.33D+02   0.0265
  3.000       0.333      3.01D+04  2.78D+03  3.29D+04  1.24D+03   0.0844       7.88D+03  2.33D+02  8.11D+03  3.05D+02   0.0287


 J. A. BEARDEN AND A. F. BURR, REV. MOD. PHYS. 39, 125 (1967):
 OBSERVED BINDING ENERGIES (EV): BL1= 2865.5  BL2= 2625.1  BL3= 2520.2
 THETA =4*BL(EV)/Z2L/13.605(EV): TL1= 0.5881  TL2= 0.5387  TL3= 0.5172

 W. BAMBYNEK ET AL., REV. MOD. PHYS. 44, 716 (1972):
 SUBSHELL FLUORESCENCE YIELDS                        W1           W2           W3
                                                   0.0058       0.0356       0.0373
 COSTER-KRONIG  PROBABILITIES                        F12          F23          F13
                                                    0.166        0.124        0.689

 M. O. KRAUSE, J. PHYS. CHEM. REF. DATA 8, 307 (1979):
 SUBSHELL FLUORESCENCE YIELDS                        W1           W2           W3
                                                   0.0100       0.0340       0.0370
 COSTER-KRONIG  PROBABILITIES                        F12          F23          F13
                                                    0.100        0.141        0.610

 UNOCCUPIED K,L,M,N FRACTIONS FOR  Q =  1.00 : 0.000 0.875 1.000 1.000
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*JUNE  1985                                                                                  G. LAPICKI   EAST CAROLINA UNIVERSITY
=====================================================================================================================================

Z1=  4     Z2= 47                                     ****  L-SHELL CROSS SECTIONS (BARNS) ****
 FLUORESCENCE & COSTER-KRONIG YIELDS FROM KRAUSE [1979]
                                 FIRST BORN APPROXIMATION                                           ECPSSR THEORY
-------------------------------------------------------------------------------------------------------------------------------------
 E1(MEV) E1(MEV)/A1(U)  DIRECT + CAPTURE = IONIZATION XRAY PROD.  C/I            DIRECT + CAPTURE = IONIZATION XRAY PROD.  C/I
-------------------------------------------------------------------------------------------------------------------------------------
  0.250       0.028     3.48D+00  2.17D-02  3.50D+00  1.86D-01   0.0062          9.33D-04  6.15D-06  9.39D-04  4.96D-05   0.0066
  0.500       0.056     4.42D+01  3.75D-01  4.46D+01  2.48D+00   0.0080          7.49D-01  4.38D-03  7.53D-01  3.99D-02   0.0058
  0.750       0.083     1.88D+02  1.97D+00  1.90D+02  1.01D+01   0.0104          8.80D+00  5.42D-02  8.86D+00  4.70D-01   0.0061
  1.000       0.111     4.74D+02  6.30D+00  4.81D+02  2.57D+01   0.0131          3.62D+01  2.45D-01  3.64D+01  1.94D+00   0.0067
  1.250       0.139     9.28D+02  1.53D+01  9.43D+02  5.05D+01   0.0162          9.52D+01  7.16D-01  9.59D+01  5.11D+00   0.0075
  1.500       0.167     1.56D+03  3.10D+01  1.59D+03  8.51D+01   0.0196          1.97D+02  1.65D+00  1.99D+02  1.06D+01   0.0083
  1.750       0.194     2.36D+03  5.57D+01  2.41D+03  1.29D+02   0.0231          3.51D+02  3.29D+00  3.54D+02  1.89D+01   0.0093
  2.000       0.222     3.32D+03  9.15D+01  3.41D+03  1.83D+02   0.0268          5.66D+02  5.89D+00  5.72D+02  3.06D+01   0.0103
  2.250       0.250     4.45D+03  1.40D+02  4.59D+03  2.47D+02   0.0305          8.49D+02  9.76D+00  8.59D+02  4.60D+01   0.0114
  2.500       0.278     5.74D+03  2.03D+02  5.94D+03  3.20D+02   0.0342          1.21D+03  1.52D+01  1.22D+03  6.56D+01   0.0125
  2.750       0.306     7.17D+03  2.82D+02  7.46D+03  4.01D+02   0.0379          1.64D+03  2.27D+01  1.67D+03  8.95D+01   0.0136
  3.000       0.333     8.76D+03  3.78D+02  9.14D+03  4.92D+02   0.0414          2.16D+03  3.24D+01  2.20D+03  1.18D+02   0.0148


 J. A. BEARDEN AND A. F. BURR, REV. MOD. PHYS. 39, 125 (1967):
 OBSERVED BINDING ENERGIES (EV): BL1= 3805.8  BL2= 3523.7  BL3= 3351.1
 THETA =4*BL(EV)/Z2L/13.605(EV): TL1= 0.6094  TL2= 0.5642  TL3= 0.5366


 W. BAMBYNEK ET AL., REV. MOD. PHYS. 44, 716 (1972):
                                              W1           W2           W3
 SUBSHELL FLUORESCENCE YIELDS              0.0102       0.0587       0.0602
                                              F12          F23          F13
 COSTER-KRONIG  PROBABILITIES               0.052        0.152        0.786
 M. O. KRAUSE, J. PHYS. CHEM. REF. DATA 8, 307 (1979):
                                              W1           W2           W3
 SUBSHELL FLUORESCENCE YIELDS              0.0160       0.0519       0.0520
                                              F12          F23          F13
 COSTER-KRONIG  PROBABILITIES               0.100        0.153        0.590

 UNOCCUPIED K,L,M,N FRACTIONS FOR  U =  1.00 : 0.000 0.875 1.000 1.000
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APPENDIX C

Theoretical M-shell ionization and x-ray production cross sections for incident $^{9}_{4}Be^{+}$ ions upon Pr, Nd, Eu, Gd, Dy, Ho, Yb, Hf, W, Au, Pb, Bi, and U.

```
           Z1= 4
           A1= 9.000
           EMIN= 0.25000       EMAX=    3.00000      ESTEP=    0.25000

           Z2= 59
           A2= 140.900
J. A. BEARDEN AND A. F. BURR, REV. MOD. PHYS. 39, 125 (1967): BM1= 1511.0  BM2= 1337.4  BM3= 1242.2  BM4=  951.1  BM5=  931.0
           THETA = 9 * BM(EV) / Z2M /13.605(EV) :        TM1= 0.4384  TM2= 0.3800  TM3= 0.3604  TM4= 0.4392  TM5= 0.4299

E. J. MCGUIRE, PHYS. REV. A5, 1043 (1972):
SUBSHELL FLUORESCENCE YIELDS                 W1          W2          W3          W4          W5
                                          0.000020    0.001250    0.000103    0.002600    0.002300

COSTER-KRONIG PROBABILITIES      F12     F13     F14     F15     F23     F24     F25     F34     F35     F45
                                0.229   0.499   0.042   0.132   0.069   0.615   0.255   0.142   0.701   0.233

Z1=  4    Z2= 59                        **** M-SHELL CROSS SECTIONS (BARN) ****
                          FIRST BORN APPROXIMATION                                        ECPSSR THEORY
                   ------------------------------------------------------------------------------------------------------------
E1(MEV)  KSI RELATIV.  DIRECT + CAPTURE = IONIZATION XRAY PROD.  C/I        DIRECT + CAPTURE = IONIZATION XRAY PROD.  C/I
---------------------------------------------------------------------------------------------------------------------------

0.250      0.269      9.98E+03  8.65E+02  1.08E+04  2.84E+01  0.0663      6.67E+01  2.68E+00  6.93E+01  1.83E-01   0.0381
0.500      0.381      8.46E+04  1.73E+04  1.02E+05  2.27E+02  0.1705      3.71E+03  2.90E+02  4.01E+03  1.06E+01   0.0725
0.750      0.477      2.34E+05  7.93E+04  3.13E+05  8.23E+02  0.2529      2.21E+04  2.24E+03  2.43E+04  6.39E+01   0.0921
1.000      0.568      4.19E+05  2.00E+05  6.20E+05  1.63E+03  0.3231      6.82E+04  8.28E+03  7.64E+04  2.01E+02-  0.1084
1.250      0.651      6.20E+05  3.71E+05  9.91E+05  2.60E+03  0.3784      1.48E+05  2.18E+04  1.70E+05  4.47E+02   0.1283
1.500      0.729      8.26E+05  5.72E+05  1.40E+06  3.67E+03  0.4091      2.53E+05  4.57E+04  2.99E+05  7.87E+02-  0.1528
1.750      0.804      1.04E+06  7.82E+05  1.82E+06  4.75E+03  0.4302      3.81E+05  8.09E+04  4.62E+05  1.21E+03   0.1751
2.000      0.873      1.25E+06  9.86E+05  2.24E+06  5.85E+03  0.4408      5.24E+05  1.25E+05  6.49E+05  1.71E+03-  0.1932
2.250      0.944      1.47E+06  1.17E+06  2.64E+06  6.95E+03  0.4435      6.79E+05  1.75E+05  8.54E+05  2.24E+03   0.2053
2.500      1.010      1.69E+06  1.34E+06  3.03E+06  7.99E+03  0.4411      8.43E+05  2.27E+05  1.07E+06  2.81E+03-  0.2118
2.750      1.074      1.92E+06  1.48E+06  3.40E+06  8.97E+03  0.4396      1.02E+06  2.76E+05  1.29E+06  3.40E+03   0.2137
3.000      1.135      2.15E+06  1.59E+06  3.75E+06  9.90E+03  0.4253      1.20E+06  3.23E+05  1.52E+06  4.01E+03-  0.2121
```

Pr
51

```
          Z1= 4
          A1= 9.000
          EMIN=   0.25000       EMAX=    3.00000       ESTEP=    0.25000

          Z2= 60
          A2= 144.200
J. A. BEARDEN AND A. F. BURR, REV. MOD. PHYS. 39, 125 (1967): BM1= 1575.3  BM2= 1402.8  BM3= 1297.4  BM4=  999.9  BM5=  977.7
          THETA = 9 * BM(EV) / Z2M /13.605(EV) ;        TM1= 0.4385  TM2= 0.3905  TM3= 0.3611  TM4= 0.4362  TM5= 0.4285

E. J. MCGUIRE, PHYS. REV. A5, 1043 (1972):
SUBSHELL FLUORESCENCE YIELDS
                                        W1          W2          W3          W4          W5
                                   0.000810    0.001320    0.001050    0.002600    0.003200

COSTER-KRONIG PROBABILITIES         S12    S13    S14    S15    S23    S24    S25    S34    S35    S45
                                  0.236  0.489  0.092  0.125  0.057  0.644  0.172  0.174  0.712  0.267

Z1= 4    Z2= 60
                                            **** M-SHELL CROSS SECTIONS (BARN) ****

                               FIRST BORN APPROXIMATION                                        ECPSSR THEORY                    Nd
                      -------------------------------------------------------------------------------------------------------------
E1(MEV)  KSI RELATIV.  DIRECT + CAPTURE = IONIZATION XRAY PROD.  C/I        DIRECT + CAPTURE = IONIZATION XRAY PROD.  C/I
-------------------------------------------------------------------------------------------------------------------------------------

 0.250      0.261      7.70E+03  5.80E+02  8.28E+03  2.93E+01  0.0701     4.66E+01  1.86E+00  4.82E+01  1.85E-01   0.0344
 0.500      0.374      6.72E+04  1.19E+04  7.91E+04  2.69E+02  0.1499     2.87E+03  2.01E+02  3.08E+03  1.12E+01   0.0654
 0.750      0.470      1.92E+05  5.55E+04  2.47E+05  8.35E+02  0.2246     1.73E+04  1.59E+03  1.89E+04  6.63E+01   0.0840
 1.000      0.556      3.47E+05  1.43E+05  4.91E+05  1.65E+03  0.2922     5.41E+04  5.90E+03  6.00E+04  2.07E+02   0.0984
 1.250      0.635      5.19E+05  2.71E+05  7.91E+05  2.66E+03  0.3334     1.19E+05  1.56E+04  1.35E+05  4.62E+02   0.1155
 1.500      0.713      6.95E+05  4.26E+05  1.12E+06  3.77E+03  0.3798     2.07E+05  3.29E+04  2.39E+05  8.17E+02   0.1373
 1.750      0.785      8.76E+05  5.92E+05  1.47E+06  4.94E+03  0.4034     3.14E+05  5.89E+04  3.73E+05  1.27E+03   0.1580
 2.000      0.854      1.06E+06  7.57E+05  1.82E+06  6.12E+03  0.4167     4.34E+05  9.26E+04  5.27E+05  1.79E+03   0.1757
 2.250      0.921      1.25E+06  9.13E+05  2.16E+06  7.30E+03  0.4222     5.65E+05  1.32E+05  6.97E+05  2.37E+03   0.1888
 2.500      0.985      1.44E+06  1.05E+06  2.49E+06  8.44E+03  0.4221     7.05E+05  1.73E+05  8.78E+05  2.99E+03   0.1969
 2.750      1.047      1.64E+06  1.17E+06  2.81E+06  9.55E+03  0.4178     8.54E+05  2.13E+05  1.07E+06  3.65E+03   0.1999
 3.000      1.107      1.84E+06  1.28E+06  3.11E+06  1.06E+04  0.4105     1.01E+06  2.52E+05  1.26E+06  4.32E+03   0.2000
```

63^{Eu}

```
          Z1=  4
          A1=  9.000
          EMIN=   0.25000        EMAX=    3.00000       ESTEP=    0.25000

          Z2= 63
          A2= 152.000
J. A. BEARDEN AND A. F. BURR, REV. MOD. PHYS. 39, 125 (1967): BM1= 1800.0  BM2= 1613.9  BM3= 1480.6  BM4= 1160.6  BM5= 1130.9
          THETA = 9 * BM(EV) / Z2M /13.605(EV) :        TM1= 0.4446  TM2= 0.3987  TM3= 0.3657  TM4= 0.4384  TM5= 0.4271

E. J. MCGUIRE, PHYS. REV. A5, 1043 (1972):
SUBSHELL FLUORESCENCE YIELDS                              W1          W2          W3          W4          W5
                                                  0.000070    0.001470    0.001260    0.004100    0.005900

COSTER-KRONIG PROBABILITIES         S12    S13    S14    S15    S23    S24    S25    S34    S35    S45
                                  0.338  0.445  0.070  0.100  0.062  0.514  0.137  0.165  0.728  0.369

Z1=  4    Z2= 63                                **** M-SHELL CROSS SECTIONS (BARN) ****

                              FIRST BORN APPROXIMATION                                   ECPSSR THEORY
                       ----------------------------------------------------------------------------------------------------
E1(MEV)  KSI RELATIV.  DIRECT + CAPTURE = IONIZATION XRAY PROD.  C/I         DIRECT + CAPTURE = IONIZATION XRAY PROD.  C/I
-------------------------------------------------------------------------------------------------------------------------

 0.250     0.262     3.53E+03  1.72E+02  3.70E+03  2.30E+01  0.0464     1.48E+01  3.82E-01  1.52E+01  9.68E-02   0.0252
 0.500     0.355     3.31E+04  3.72E+03  3.68E+04  2.25E+02  0.1010     1.31E+03  5.81E+01  1.37E+03  8.57E+00   0.0425
 0.750     0.443     1.01E+05  1.87E+04  1.19E+05  7.27E+02  0.1564     8.28E+03  5.61E+02  8.84E+03  5.45E+01   0.0635
 1.000     0.522     1.94E+05  5.16E+04  2.45E+05  1.49E+03  0.2101     2.67E+04  2.13E+03  2.88E+04  1.77E+02   0.0740
 1.250     0.595     3.00E+05  1.04E+05  4.04E+05  2.46E+03  0.2566     6.06E+04  5.68E+03  6.62E+04  4.05E+02   0.0857
 1.500     0.664     4.13E+05  1.72E+05  5.84E+05  3.55E+03  0.2938     1.11E+05  1.22E+04  1.23E+05  7.51E+02 - 0.0991
 1.750     0.730     5.27E+05  2.50E+05  7.78E+05  4.73E+03  0.3219     1.72E+05  2.24E+04  1.95E+05  1.19E+03   0.1149
 2.000     0.793     6.44E+05  3.34E+05  9.78E+05  5.95E+03  0.3417     2.45E+05  3.64E+04  2.81E+05  1.72E+03 - 0.1296
 2.250     0.854     7.63E+05  4.19E+05  1.18E+06  7.20E+03  0.3540     3.25E+05  5.40E+04  3.79E+05  2.31E+03   0.1425
 2.500     0.913     8.85E+05  5.00E+05  1.39E+06  8.44E+03  0.3608     4.10E+05  7.39E+04  4.84E+05  2.96E+03   0.1527
 2.750     0.969     1.01E+06  5.75E+05  1.58E+06  9.66E+03  0.3630     5.02E+05  9.51E+04  5.97E+05  3.64E+03   0.1594
 3.000     1.024     1.14E+06  6.44E+05  1.78E+06  1.09E+04  0.3617     5.97E+05  1.17E+05  7.14E+05  4.36E+03   0.1633
```

$_{64}$Gd

```
            Z1=  4
            A1=  9.000
            EMIN=   0.25000       EMAX=    3.00000      ESTEP=    0.25000

            Z2= 64
            A2= 157.300
J. A. BEARDEN AND A. F. BURR, REV. MOD. PHYS. 39, 125 (1967): BM1= 1880.8  BM2= 1688.3  BM3= 1544.0  BM4= 1217.2  BM5= 1185.2
            THETA = 9 * BM(EV) / Z2M /13.605(EV) :       TM1= 0.4471  TM2= 0.4014  TM3= 0.3671  TM4= 0.4365  TM5= 0.4270

E. J. MCGUIRE, PHYS. REV. A5, 1043 (1972):
SUBSHELL FLUORESCENCE YIELDS                     W1          W2          W3          W4          W5
                                            0.000920    0.001570    0.001310    0.004750    0.007100

COSTER-KRONIG PROBABILITIES         S12   S13   S14   S15   S23   S24   S25   S34   S35   F45
                                  0.320 0.496 0.068 0.098 0.073 0.552 0.133 0.160 0.728 0.379

Z1=  4    Z2= 64                           **** M-SHELL CROSS SECTIONS (BARN) ****

                         FIRST BORN APPROXIMATION                                          ECPSSR THEORY
-------------------------------------------------------------------------------------------------------------------------
E1(MEV)  KSI RELATIV.  DIRECT + CAPTURE = IONIZATION XRAY PROD.  C/I        DIRECT + CAPTURE = IONIZATION XRAY PROD.  C/I
-------------------------------------------------------------------------------------------------------------------------

 0.250      0.245      2.74E+03  1.16E+02  2.86E+03  2.11E+01  0.0407      1.01E+01  2.36E-01  1.03E+01  7.81E-02  0.0228
 0.500      0.349      2.62E+04  2.56E+03  2.88E+04  2.10E+02  0.0888      1.01E+03  4.52E+01  1.05E+03  7.84E+00  0.0428
 0.750      0.434      8.11E+04  1.31E+04  9.42E+04  6.85E+02  0.1393      6.53E+03  4.01E+02  6.93E+03  5.10E+01  0.0579
 1.000      0.511      1.60E+05  3.69E+04  1.97E+05  1.43E+03  0.1875      2.12E+04  1.54E+03  2.28E+04  1.67E+02  0.0677
 1.250      0.582      2.51E+05  7.54E+04  3.26E+05  2.37E+03  0.2314      4.87E+04  4.11E+03  5.28E+04  3.86E+02  0.0777
 1.500      0.650      3.48E+05  1.27E+05  4.75E+05  3.45E+03  0.2677      9.03E+04  8.84E+03  9.92E+04  7.24E+02  0.0892
 1.750      0.714      4.47E+05  1.88E+05  6.35E+05  4.61E+03  0.2964      1.42E+05  1.63E+04  1.58E+05  1.15E+03  0.1034
 2.000      0.775      5.48E+05  2.55E+05  8.02E+05  5.83E+03  0.3172      2.03E+05  2.68E+04  2.30E+05  1.68E+03  0.1169
 2.250      0.834      6.51E+05  3.23E+05  9.74E+05  7.08E+03  0.3313      2.71E+05  4.02E+04  3.11E+05  2.27E+03  0.1292
 2.500      0.890      7.56E+05  3.89E+05  1.15E+06  8.33E+03  0.3399      3.44E+05  5.57E+04  4.00E+05  2.91E+03  0.1394
 2.750      0.945      8.63E+05  4.53E+05  1.32E+06  9.58E+03  0.3440      4.22E+05  7.26E+04  4.95E+05  3.61E+03  0.1468
 3.000      0.998      9.72E+05  5.11E+05  1.48E+06  1.08E+04  0.3446      5.04E+05  9.00E+04  5.94E+05  4.33E+03  0.1515
```

```
            Z1=  4.
            A1=  9.000
            E1I=  0.25000       EMAX=    3.00000      ESTEP=    0.25000

            Z2= 66
            A2= 162.500
J. A. BEARDEN AND A. F. BURR, REV. MOD. PHYS. 39, 125 (1967): BM1= 2046.8  BM2= 1841.8  BM3= 1675.6  BM4= 1332.5  BM5= 1294.9
            THETA = 9 * BM(EV) / Z2M /13.605(EV) :       TM1= 0.4517  TM2= 0.4065  TM3= 0.3698  TM4= 0.4382  TM5= 0.4258

E. J. MCGUIRE, PHYS. REV. A5, 1043 (1972):
SUBSHELL FLUORESCENCE YIELDS                     W1          W2          W3          W4          W5
                                              0.001030    0.001760    0.001400    0.006050    0.009400

COSTER-KRONIG PROBABILITIES          S12    S13    S14    S15    S23    S24    S25    S34    S35    S45
                                    0.284  0.516  0.063  0.093  0.095  0.629  0.124  0.150  0.743  0.399

Z1=  4     Z2= 66                              **** M-SHELL CROSS SECTIONS (BARN) ****

                           FIRST BORN APPROXIMATION                                              ECPSSR THEORY
                   -------------------------------------------------------------------------------------------------------------
E1(MEV)  KSI RELATIV.  DIRECT + CAPTURE = IONIZATION XRAY PROD.   C/I          DIRECT + CAPTURE = IONIZATION XRAY PROD.   C/I
-------------------------------------------------------------------------------------------------------------------------------

 0.250       0.238     1.70E+03  5.56E+01  1.75E+03  1.71E+01  0.0318       4.61E+00  8.95E-02  4.70E+00  4.64E-02   0.0190
 0.500       0.336     1.69E+04  1.26E+03  1.81E+04  1.75E+02  0.0694       6.09E+02  2.20E+01  6.31E+02  6.18E+00   0.0349
 0.750       0.423     5.40E+04  6.66E+03  6.07E+04  5.83E+02  0.1099       4.14E+03  2.10E+02  4.35E+03  4.22E+01   0.0483
 1.000       0.492     1.11E+05  1.94E+04  1.30E+05  1.25E+03  0.1491       1.37E+04  8.27E+02  1.45E+04  1.40E+02   0.0569
 1.250       0.560     1.77E+05  4.11E+04  2.18E+05  2.09E+03  0.1885       3.20E+04  2.22E+03  3.42E+04  3.30E+02   0.0649
 1.500       0.624     2.49E+05  7.13E+04  3.21E+05  3.08E+03  0.2222       6.05E+04  4.82E+03  6.53E+04  6.29E+02 - 0.0739
 1.750       0.684     3.25E+05  1.08E+05  4.33E+05  4.15E+03  0.2502       9.70E+04  9.01E+03  1.06E+05  1.02E+03   0.0850
 2.000       0.742     4.02E+05  1.50E+05  5.52E+05  5.29E+03  0.2722       1.41E+05  1.50E+04  1.56E+05  1.50E+03 - 0.0962
 2.250       0.795     4.79E+05  1.95E+05  6.74E+05  6.47E+03  0.2887       1.91E+05  2.28E+04  2.14E+05  2.05E+03   0.1069
 2.500       0.851     5.59E+05  2.40E+05  7.99E+05  7.67E+03  0.3001       2.45E+05  3.23E+04  2.77E+05  2.67E+03   0.1168
 2.750       0.903     6.40E+05  2.84E+05  9.24E+05  8.87E+03  0.3073       3.03E+05  4.30E+04  3.46E+05  3.32E+03   0.1244
 3.000       0.953     7.22E+05  3.26E+05  1.05E+06  1.01E+04  0.3110       3.64E+05  5.44E+04  4.18E+05  4.02E+03   0.1301
```

Dy 66

$_{67}Ho$

```
         Z1=  4
         A1=  9.000
         EMIN=    0.25000       EMAX=    3.00000       ESTEP=    0.25000

         Z2= 67
         A2= 164.900
J. A. BEARDEN AND A. F. BURR, REV. MOD. PHYS. 39, 125 (1967); BM1= 2128.3  BM2= 1922.8  BM3= 1741.2  BM4= 1391.5  BM5= 1351.4
         THETA = 9 * BM(EV) / Z2** /13.605(EV) :                      TM1= 0.4530  TM2= 0.4092  TM3= 0.3705  TM4= 0.4379  TM5= 0.4293

E. J. MCGUIRE, PHYS. REV. A5, 1043 (1972):                     W1          W2          W3          W4          W5
SUBSHELL FLUORESCENCE YIELDS                               0.001000    0.001050    0.001450    0.006700    0.010600

                                        S12     S13     S14     S15     S23     S24     S25     S34     S35     F45
COSTER-KRONIG PROBABILITIES           0.266   0.527   0.061   0.090   0.106   0.667   0.120   0.145   0.751   0.408

                                                  **** M-SHELL CROSS SECTIONS (BARN) ****

Z1=  4    Z2= 67
                                                                                                  ECPSSR THEORY
                                         FIRST BORN APPROXIMATION
                                                                                    DIRECT + CAPTURE = IONIZATION XRAY PROD.   C/I
E1(MEV)   KSI RELATIV.   DIRECT + CAPTURE = IONIZATION XRAY PROD.   C/I

 0.250      0.235       1.35E+03  3.92E+01  1.39E+03  1.53E+01  0.0203     3.14E+00  5.58E-02  3.19E+00  3.54E-02  0.0175
 0.500      0.333       1.36E+04  8.95E+02  1.45E+04  1.58E+02  0.0617     4.75E+02  1.56E+01  4.91E+02  5.42E+00  0.0318
 0.750      0.413       4.43E+04  4.81E+03  4.91E+04  5.32E+02  0.0980     3.32E+03  1.54E+02  3.47E+03  3.80E+01  0.0443
 1.000      0.484       9.26E+04  1.43E+04  1.07E+05  1.16E+03  0.1333     1.11E+04  6.14E+02  1.17E+04  1.27E+02  0.0524
 1.250      0.550       1.49E+05  3.06E+04  1.80E+05  1.94E+03  0.1700     2.61E+04  1.66E+03  2.78E+04  3.02E+02  0.0596
 1.500      0.612       2.12E+05  5.37E+04  2.66E+05  2.87E+03  0.2021     4.96E+04  3.60E+03  5.32E+04  5.76E+02  0.0677
 1.750      0.671       2.78E+05  8.27E+04  3.61E+05  3.90E+03  0.2292     8.10E+04  6.76E+03  8.78E+04  9.52E+02  0.0770
 2.000      0.727       3.45E+05  1.16E+05  4.61E+05  4.96E+03  0.2516     1.16E+05  1.13E+04  1.29E+05  1.40E+03  0.0874
 2.250      0.781       4.14E+05  1.52E+05  5.65E+05  6.12E+03  0.2665     1.61E+05  1.74E+04  1.78E+05  1.93E+03  0.0973
 2.500      0.833       4.83E+05  1.89E+05  6.72E+05  7.27E+03  0.2809     2.08E+05  2.47E+04  2.32E+05  2.56E+03  0.1065
 2.750      0.884       5.54E+05  2.25E+05  7.79E+05  8.43E+03  0.2893     2.55E+05  3.32E+04  2.91E+05  3.15E+03  0.1142
 3.000      0.733       6.26E+05  2.61E+05  8.87E+05  9.60E+03  0.2943     3.10E+05  4.25E+04  3.53E+05  3.83E+03  0.1203
```

70 Yb

```
Z1=  4
A1=  9.000
EMIN=    0.25000       EMAX=    3.00000      ESTEP=    0.25000

Z2= 70
A2= 173.000

J. A. BEARDEN AND A. F. BURR, REV. MOD. PHYS. 39, 125 (1967): BM1= 2398.1  BM2= 2173.0  BM3= 1949.3  BM4= 1576.3  BM5= 1527.8
          THETA = 9 * BM(EV) / Z2M /13.605(EV) :         TM1= 0.4596  TM2= 0.4165  TM3= 0.3737  TM4= 0.4370  TM5= 0.4235

L. J. MCGUIRE, PHYS. REV. A5, 1043 (1972):
SUBSHELL FLUORESCENCE YIELDS                          W1          W2          W3          W4          W5
                                                0.001150    0.001970    0.001660    0.008600    0.014900

                                    S12    S13    S14    S15    S23    S24    S25    S34    S35    S45
COSTER-KRONIG PROBABILITIES       0.272  0.529  0.056  0.091  0.116  0.680  0.155  0.141  0.761  0.479

Z1=  4    Z2= 70                                    **** M-SHELL CROSS SECTIONS (BARN) ****
                            FIRST BORN APPROXIMATION                                               ECPSSR THEORY
                    ******************************************************************************************************
E1(MEV)  KSI RELATIV.  DIRECT + CAPTURE = IONIZATION XRAY PROD.  C/I          DIRECT + CAPTURE = IONIZATION XRAY PROD.  C/I
--------------------------------------------------------------------------------------------------------------------------

 0.250       0.226      6.89E+02  1.42E+01  7.03E+02  1.08E+01  0.0202       9.50E-01  1.32E-02  9.64E-01  1.48E-02  0.0137
 0.500       0.319      7.29E+03  3.34E+02  7.63E+03  1.17E+02  0.0438       2.27E+02  5.57E+00  2.32E+02  3.58E+00  0.0240
 0.750       0.394      2.42E+04  1.87E+03  2.61E+04  4.07E+02  0.0701       1.74E+03  6.16E+01  1.80E+03  2.77E+01  0.0341
 1.000       0.460      5.37E+04  5.77E+03  5.94E+04  9.06E+02  0.0971       6.00E+03  2.57E+02  6.26E+03  9.56E+01  0.0411
 1.250       0.522      9.03E+04  1.29E+04  1.03E+05  1.57E+03  0.1240       1.45E+04  7.08E+02  1.52E+04  2.32E+02  0.0467
 1.500       0.579      1.32E+05  2.35E+04  1.55E+05  2.37E+03  0.1513       2.81E+04  1.56E+03  2.96E+04  4.52E+02  0.0525
 1.750       0.634      1.76E+05  3.74E+04  2.13E+05  3.25E+03  0.1753       4.73E+04  2.95E+03  5.02E+04  7.67E+02  0.0587
 2.000       0.686      2.22E+05  5.41E+04  2.76E+05  4.21E+03  0.1960       7.03E+04  5.01E+03  7.53E+04  1.15E+03  0.0665
 2.250       0.738      2.68E+05  7.29E+04  3.41E+05  5.20E+03  0.2137       9.75E+04  7.81E+03  1.05E+05  1.61E+03  0.0742
 2.500       0.785      3.16E+05  9.30E+04  4.09E+05  6.23E+03  0.2276       1.28E+05  1.14E+04  1.39E+05  2.13E+03  0.0815
 2.750       0.831      3.64E+05  1.14E+05  4.77E+05  7.28E+03  0.2384       1.61E+05  1.56E+04  1.76E+05  2.69E+03  0.0884
 3.000       0.877      4.12E+05  1.35E+05  5.47E+05  8.35E+03  0.2462       1.96E+05  2.04E+04  2.16E+05  3.30E+03  0.0944
```

72 Hf

```
          Z1=  4
          A1=  9.000
          EMIN=   0.25000        EMAX=    3.00000       ESTEP=    0.25000

          Z2= 72
          A2= 178.500
J. A. BEARDEN AND A. F. BURR, REV. MOD. PHYS. 39, 125 (1967): BM1= 2600.9  BM2= 2365.4  BM3= 2107.6  BM4= 1716.4  BM5= 1661.7
          THETA = 9 * BM(EV) / Z2M /13.605(EV) :       TH1= 0.4662  TH2= 0.4240  TH3= 0.3778  TH4= 0.4391  TH5= 0.4251

E. J. MCGUIRE, PHYS. REV. A5, 1043 (1972):
SUBSHELL FLUORESCENCE YIELDS                    W1          W2          W3          W4          W5
                                            0.001350    0.002420    0.001980    0.011500    0.018600

COSTER-KRONIG PROBABILITIES          F12    F13    F14    F15    F23    F24    F25    F34    F35    F45
                                    0.222  0.549  0.061  0.107  0.115  0.676  0.106  0.102  0.794  0.434

Z1=  4    Z2= 72                                 **** M-SHELL CROSS SECTIONS (BARN) ****

                            FIRST BORN APPROXIMATION                                         FCPSSR THEORY
                    ----------------------------------------------------------------------------------------------------------
EI(MEV)  KSI RELATIV.  DIRECT + CAPTURE = IONIZATION XRAY PROD.  C/I        DIRECT + CAPTURE = IONIZATION XRAY PROD.  C/I
----------------------------------------------------------------------------------------------------------------------------

 0.250      0.220      4.27E+02  6.99E+00  4.34E+02  8.25E+00  0.0161       3.95E-01  4.67E-03  3.99E-01  7.58E-03  0.0117
 0.500      0.309      4.67E+03  1.67E+02  4.84E+03  9.19E+01  0.0345       1.33E+02  2.67E+00  1.35E+02  2.58E+00  0.0197
 0.750      0.381      1.64E+04  9.59E+02  1.73E+04  3.25E+02  0.0554       1.10E+03  3.21E+01  1.14E+03  2.16E+01  0.0283
 1.000      0.444      3.62E+04  3.04E+03  3.93E+04  7.45E+02  0.0774       3.89E+03  1.39E+02  4.03E+03  7.66E+01  0.0346
 1.250      0.502      6.34E+04  6.96E+03  7.04E+04  1.34E+03  0.0989       9.52E+03  3.91E+02  9.91E+03  1.86E+02  0.0394
 1.500      0.557      9.37E+04  1.30E+04  1.07E+05  2.03E+03  0.1220       1.88E+04  8.65E+02  1.96E+04  3.73E+02  0.0441
 1.750      0.608      1.27E+05  2.12E+04  1.48E+05  2.82E+03  0.1430       3.19E+04  1.65E+03  3.36E+04  6.38E+02  0.0491
 2.000      0.658      1.62E+05  3.14E+04  1.93E+05  3.67E+03  0.1621       4.90E+04  2.83E+03  5.18E+04  9.84E+02  0.0546
 2.250      0.705      1.98E+05  4.31E+04  2.41E+05  4.58E+03  0.1788       6.83E+04  4.45E+03  7.28E+04  1.38E+03  0.0612
 2.500      0.751      2.34E+05  5.61E+04  2.90E+05  5.51E+03  0.1931       9.07E+04  6.55E+03  9.73E+04  1.85E+03  0.0674
 2.750      0.796      2.71E+05  6.98E+04  3.41E+05  6.48E+03  0.2046       1.15E+05  9.12E+03  1.24E+05  2.36E+03  0.0733
 3.000      0.838      3.09E+05  8.40E+04  3.93E+05  7.46E+03  0.2138       1.41E+05  1.21E+04  1.53E+05  2.91E+03  0.0788
```

```
Z1=  4
A1=  9.000
EMIN=   0.25000       EMAX=    3.00000      ESTEP=    0.25000

Z2= 74
A2= 183.900
J. A. BEARDEN AND A. F. BURR, REV. MOD. PHYS. 39, 125 (1967): BM1= 2819.6  BM2= 2574.9  BM3= 2281.0  BM4= 1871.6  BM5= 1809.2
            THETA = 0 * BM(EV) / Z2M /13.605(EV) :        TM1= 0.4737  TM2= 0.4326  TM3= 0.3632  TM4= 0.4433  TM5= 0.4285

E. J. MCGUIRE, PHYS. REV. A5, 1043 (1972):
SUBSHELL FLUORESCENCE YIELDS                          W1           W2           W3           W4           W5
                                               0.001520     0.002640     0.002400     0.013200     0.021400

COSTER-KRONIG PROBABILITIES          S12    S13    S14    S15    S23    S24    S25    S34    S35    F45
                                   0.185  0.572  0.066  0.113  0.112  0.677  0.103  0.090  0.795  0.413

Z1=  4    Z2= 74                              **** M-SHELL CROSS SECTIONS (BARN) ****
                              FIRST BORN APPROXIMATION                                   ECPSSR THEORY
                          -------------------------------------------------------------------------------------------------------
E1(MEV). KSI RELATIV.     DIRECT + CAPTURE = IONIZATION XRAY PROD.  C/I            DIRECT + CAPTURE = IONIZATION XRAY PROD.  C/I
------------------------------------------------------------------------------------------------------------------------------------

  0.250      0.215     2.60E+02  3.38E+00  2.63E+02  5.72E+00    0.0128       1.54E-01  1.55E-03  1.55E-01  3.36E-03    0.0100
  0.500      0.299     2.94E+03  8.16E+01  3.02E+03  6.55E+01    0.0270       7.54E+01  1.24E+00  7.66E+01  1.66E+00    0.0162
  0.750      0.360     1.06E+04  4.80E+02  1.11E+04  2.40E+02    0.0434       6.86E+02  1.64E+01  7.02E+02  1.53E+01    0.0233
  1.000      0.426     2.41E+04  1.56E+03  2.57E+04  5.56E+02    0.0608       2.49E+03  7.41E+01  2.56E+03  5.57E+01    0.0289
  1.250      0.483     4.32E+04  3.67E+03  4.69E+04  1.02E+03    0.0782       6.18E+03  2.12E+02  6.39E+03  1.39E+02    0.0331
  1.500      0.534     6.55E+04  7.03E+03  7.26E+04  1.57E+03    0.0968       1.24E+04  4.70E+02  1.28E+04  2.78E+02    0.0369
  1.750      0.583     9.04E+04  1.17E+04  1.02E+05  2.21E+03    0.1148       2.13E+04  9.10E+02  2.22E+04  4.82E+02    0.0409
  2.000      0.630     1.17E+05  1.77E+04  1.35E+05  2.91E+03    0.1314       3.33E+04  1.57E+03  3.49E+04  7.55E+02    0.0450
  2.250      0.674     1.44E+05  2.48E+04  1.69E+05  3.66E+03    0.1469       4.74E+04  2.50E+03  4.99E+04  1.08E+03    0.0500
  2.500      0.717     1.72E+05  3.29E+04  2.05E+05  4.44E+03    0.1605       6.35E+04  3.71E+03  6.72E+04  1.46E+03    0.0552
  2.750      0.759     2.01E+05  4.17E+04  2.42E+05  5.25E+03    0.1722       8.15E+04  5.22E+03  8.67E+04  1.86E+03    0.0602
  3.000      0.800     2.29E+05  5.10E+04  2.80E+05  6.07E+03    0.1819       1.01E+05  7.02E+03  1.08E+05  2.34E+03    0.0650
```

74W

79Au

```
         Z1=  4.
         A1=  9.000
         EMIN=   0.25000        EMAX=    3.00000      ESTEP=     0.25000

         Z2= 79
         A2= 197.000
J. A. BEARDEN AND A. F. BURR, REV. MOD. PHYS. 39, 125 (1967): BM1= 3424.9  BM2= 3147.8  BM3= 2743.0  BM4= 2291.1  BM5= 2205.7
         THETA = 9 * BM(EV) / Z2M /13.605(EV) ;           TM1= 0.4936  TM2= 0.4537  TM3= 0.3953  TM4= 0.4529  TM5= 0.4360

E. J. MCGUIRE, PHYS. REV. A5, 1043 (1972):
SUBSHELL FLUORESCENCE YIELDS                              W1           W2           W3           W4           W5
                                                     0.002130     0.004230     0.004200     0.026400     0.025600

COSTER-KRONIG PROBABILITIES          S12    S13    S14    S15    S23    S24    S25    S34    S35    S45
                                   0.148  0.594  0.067  0.112  0.114  0.673  0.095  0.114  0.732  0.046

Z1=  4     Z2= 79                                        **** M-SHELL CROSS SECTIONS (BARN) ****

                                FIRST BORN APPROXIMATION                                           FCPSSR THEORY
                         ---------------------------------------------------------------------------------------------------------
E1(MEV)  KSI RELATIV.   DIRECT + CAPTURE = IONIZATION XRAY PROD.   C/I         DIRECT + CAPTURE = IONIZATION XRAY PROD.   C/I
----------------------------------------------------------------------------------------------------------------------------------

  0.250       0.190      7.99E+01  6.23E-01  8.05E+01  2.19E+00   0.0077       1.34E-02  9.47E-05  1.35E-02  3.65E-04   0.0070
  0.500       0.277      9.76E+02  1.54E+01  9.93E+02  2.46E+01   0.0155       1.42E+01  1.91E-01  1.44E+01  4.49E-01   0.0134
  0.750       0.353      3.73E+03  9.43E+01  3.82E+03  1.02E+02   0.0247       2.16E+02  3.24E+00  2.19E+02  5.90E+00   0.0148
  1.000       0.393      8.93E+03  3.22E+02  9.30E+03  2.47E+02   0.0346       8.57E+02  1.64E+01  8.73E+02  2.34E+01   0.0188
  1.250       0.441      1.69E+04  7.96E+02  1.77E+04  4.67E+02   0.0451       2.22E+03  4.97E+01  2.27E+03  6.06E+01   0.0219
  1.500       0.487      2.72E+04  1.60E+03  2.88E+04  7.63E+02   0.0556       4.58E+03  1.15E+02  4.69E+03  1.25E+02   0.0245
  1.750       0.530      3.94E+04  2.80E+03  4.23E+04  1.12E+03   0.0664       8.14E+03  2.25E+02  8.36E+03  2.22E+02   0.0269
  2.000       0.571      5.24E+04  4.43E+03  5.69E+04  1.50E+03   0.0779       1.30E+04  3.94E+02  1.34E+04  3.56E+02   0.0294
  2.250       0.610      6.66E+04  6.09E+03  7.31E+04  1.93E+03   0.0888       1.93E+04  6.36E+02  1.99E+04  5.29E+02   0.0319
  2.500       0.647      8.14E+04  8.96E+03  9.04E+04  2.39E+03   0.0991       2.69E+04  9.63E+02  2.79E+04  7.39E+02   0.0346
  2.750       0.684      9.66E+04  1.18E+04  1.08E+05  2.87E+03   0.1068       3.52E+04  1.38E+03  3.66E+04  9.71E+02   0.0378
  3.000       0.719      1.12E+05  1.50E+04  1.27E+05  3.36E+03   0.1177       4.46E+04  1.90E+03  4.65E+04  1.23E+03   0.0409
```

428

```
          Z1=  4
          A1=  9.000
          EMIN=    0.25000       EMAX=    3.00000       ESTEP=    0.25000

          Z2= 82
          A2= 207.200
J. A. BEARDEN AND A. F. BURR, REV. MOD. PHYS. 39, 125 (1967): BM1= 3850.7  BM2= 3554.2  BM3= 3066.4  BM4= 2585.6  BM5= 2484.0
          THETA = 9 * BM(EV) / Z2M /13.605(EV) ;          TM1= 0.5089  TM2= 0.4697  TM3= 0.4052  TM4= 0.4619  TM5= 0.4438

E. J. MCGUIRE, PHYS. REV. A5, 1043 (1972):
SUBSHELL FLUORESCENCE YIELDS                         W1          W2          W3          W4          W5
                                                0.002700    0.005950    0.005050    0.031350    0.030780

COSTER-KRONIG PROBABILITIES          F12    F13    F14    F15    F23    F24    F25    F34    F35    F45
                                   0.119  0.636  0.066  0.099  0.106  0.665  0.086  0.099  0.758  0.038

Z1=  4    Z2= 82                              **** M-SHELL CROSS SECTIONS (BARN) ****

                              FIRST BORN APPROXIMATION                                          ECPSSR THEORY
                       ------------------------------------------------------------------------------------------------------------
EI(MEV)  KSI RELATIV.  DIRECT + CAPTURE = IONIZATION XRAY PROD.  C/I          DIRECT + CAPTURE = IONIZATION XRAY PROD.  C/I
-----------------------------------------------------------------------------------------------------------------------------------

 0.250      0.189      3.82E+01  2.22E-01  3.84E+01  1.22E+00  0.0058       2.58E-03  1.50E-05  2.59E-03  8.20E-05  0.0058
 0.500      0.264      4.91E+02  5.52E+00  4.97E+02  1.57E+01  0.0111       7.14E+00  5.77E-02  7.20E+00  2.28E-01  0.0080
 0.750      0.323      1.94E+03  3.45E+01  1.97E+03  6.22E+01  0.0175       1.03E+02  1.17E+00  1.04E+02  3.30E+00  0.0112
 1.000      0.372      4.81E+03  1.21E+02  4.93E+03  1.55E+02  0.0245       4.40E+02  6.38E+00  4.46E+02  1.41E+01  0.0143
 1.250      0.413      9.29E+03  3.07E+02  9.60E+03  3.02E+02  0.0320       1.18E+03  2.02E+01  1.20E+03  3.76E+01  0.0169
 1.500      0.460      1.54E+04  6.34E+02  1.60E+04  5.03E+02  0.0397       2.47E+03  4.79E+01  2.52E+03  7.95E+01  0.0190
 1.750      0.499      2.29E+04  1.14E+03  2.41E+04  7.58E+02  0.0473       4.47E+03  9.54E+01  4.56E+03  1.44E+02  0.0209
 2.000      0.537      3.16E+04  1.85E+03  3.34E+04  1.05E+03  0.0552       7.26E+03  1.69E+02  7.43E+03  2.34E+02  0.0227
 2.250      0.573      4.07E+04  2.77E+03  4.34E+04  1.37E+03  0.0638       1.09E+04  2.75E+02  1.12E+04  3.52E+02  0.0246
 2.500      0.608      5.05E+04  3.92E+03  5.44E+04  1.71E+03  0.0719       1.55E+04  4.20E+02  1.59E+04  5.00E+02  0.0265
 2.750      0.641      6.08E+04  5.27E+03  6.61E+04  2.06E+03  0.0798       2.09E+04  6.10E+02  2.15E+04  6.76E+02  0.0284
 3.000      0.674      7.14E+04  6.82E+03  7.82E+04  2.46E+03  0.0872       2.67E+04  8.47E+02  2.76E+04  8.69E+02  0.0307
```

```
            Z1=  4
            A1=  9.000
            EMIN=  0.25000       EMAX=   3.00000      ESTEP=   0.25000

            Z2= 83
            A2= 209.000
J. A. BEARDEN AND A. F. BURR, REV. MOD. PHYS. 39, 125 (1967): BM1= 3999.1  BM2= 3696.3  BM3= 3176.9  BM4= 2687.6  BM5= 2579.6
            THETA = 9 * BM(EV) / Z2M /13.605(EV) :       TM1= 0.5139  TM2= 0.4750  TM3= 0.4082  TM4= 0.4640  TM5= 0.4461

E. J. MCGUIRE, PHYS. REV. A5, 1043 (1972):
SUBSHELL FLUORESCENCE YIELDS                    W1          W2          W3          W4          W5
                                          0.002090    0.006520    0.005330    0.053000    0.032500

COSTER-KRONIG PROBABILITIES       S12    S13    S14    S15    S23    S24    S25    S34    S35    S45
                                0.109  0.650  0.065  0.095  0.103  0.662  0.033  0.094  0.750  0.035

Z1=  4     Z2= 83                                  **** M-SHELL CROSS SECTIONS (BARN) ****

                              FIRST BORN APPROXIMATION                                        ECPSSR THEORY
E1(MEV)  KSI RELATIV. DIRECT + CAPTURE = IONIZATION XRAY PROD.  Z7I          DIRECT + CAPTURE = IONIZATION XRAY PROD.  Z7I
------------------------------------------------------------------------------------------------------------------------------

 0.250      0.186      3.01E+01  1.60E-01  3.03E+01  1.01E+00   0.0053       1.46E-03  8.06E-06  1.49E-03  4.90E-05   0.0054
 0.500      0.249      3.95E+02  3.99E+00  3.99E+02  1.32E+01   0.0100       5.22E+00  3.90E-02  5.26E+00  1.74E-01   0.0074
 0.750      0.317      1.57E+03  2.51E+01  1.60E+03  5.29E+01   0.0157       8.06E+01  8.39E-01  8.15E+01  2.70E+00   0.0103
 1.000      0.346      3.93E+03  8.85E+01  4.02E+03  1.33E+02   0.0220       3.54E+02  4.71E+00  3.58E+02  1.19E+01   0.0131
 1.250      0.411      7.66E+03  2.26E+02  7.89E+03  2.61E+02   0.0287       9.57E+02  1.51E+01  9.72E+02  3.22E+01   0.0156
 1.500      0.452      1.27E+04  4.71E+02  1.32E+04  4.38E+02   0.0356       2.02E+03  3.62E+01  2.06E+03  6.83E+01   0.0176
 1.750      0.490      1.92E+04  8.52E+02  2.00E+04  6.63E+02   0.0426       3.68E+03  7.25E+01  3.75E+03  1.24E+02   0.0193
 2.000      0.527      2.67E+04  1.39E+03  2.81E+04  9.31E+02   0.0495       6.02E+03  1.24E+02  6.15E+03  2.04E+02   0.0210
 2.250      0.562      3.46E+04  2.10E+03  3.67E+04  1.22E+03   0.0573       9.06E+03  2.10E+02  9.29E+03  3.08E+02   0.0226
 2.500      0.596      4.32E+04  2.99E+03  4.62E+04  1.53E+03   0.0648       1.29E+04  3.22E+02  1.32E+04  4.36E+02   0.0244
 2.750      0.629      5.23E+04  4.05E+03  5.63E+04  1.87E+03   0.0720       1.75E+04  4.69E+02  1.80E+04  5.95E+02   0.0261
 3.000      0.660      6.16E+04  5.26E+03  6.69E+04  2.22E+03   0.0790       2.27E+04  6.54E+02  2.33E+04  7.73E+02   0.0280
```

```
      Z1=  4
      A1=  9.000
      EMIN=    0.25000        EMAX=    3.00500        ESTEP=    0.25000

      Z2= 92
      A2= 238.000
J. A. BEARDEN AND A. F. BURR, REV. MOD. PHYS. 39, 125 (1967): BM1= 5548.0  BM2= 5182.2  BM3= 4303.4  BM4= 3727.6  BM5= 3551.7
      THETA = 9 * BM(EV) / Z2M /13.605(EV) :        TM1= 0.5629  TM2= 0.5257  TM3= 0.4366  TM4= 0.4912  TM5= 0.4681

E. J. MCGUIRE, PHYS. REV. A5, 1043 (1972):
SUBSHELL FLUORESCENCE YIELDS              W1          W2          W3          W4          W5
                                    0.00482     0.01613     0.00906     0.06955     0.05645

                                F12    F13    F14    F15    F23    F24    F25    F34    F35    F45
COSTER-KRONIG PROBABILITIES   0.036  0.738  0.060  0.087  0.110  0.630  0.065  0.110  0.703  0.066

Z1=  4    Z2= 92                          **** M-SHELL CROSS SECTIONS (BARN) ****

                         FIRST BORN APPROXIMATION                                     ECPSSR THEORY
                   ---------------------------------------------------------------------------------------------------------
EI(MEV)  KSI RELATIV.  DIRECT + CAPTURE = IONIZATION XRAY PROD.  C/I        DIRECT + CAPTURE = IONIZATION XRAY PROD.  C/I
---------------------------------------------------------------------------------------------------------------------------

 0.250      0.165      3.76E+00  9.60E-03  3.77E+00  2.21E-01  0.0026      6.14E-06  2.08E-08  6.16E-06  3.53E-07  0.0034
 0.500      0.228      5.75E+01  2.45E-01  5.77E+01  3.44E+00  0.0042      2.73E-01  1.06E-03  2.74E-01  1.61E-02  0.0039
 0.750      0.277      2.50E+02  1.60E+00  2.51E+02  1.51E+01  0.0064      8.46E+00  4.27E-02  8.50E+00  5.04E-01  0.0050
 1.000      0.319      6.68E+02  5.93E+00  6.74E+02  4.09E+01  0.0088      5.01E+01  3.16E-01  5.04E+01  3.02E+00  0.0063
 1.250      0.356      1.39E+03  1.60E+01  1.40E+03  8.56E+01  0.0114      1.56E+02  1.18E+00  1.58E+02  9.52E+00  0.0075
 1.500      0.391      2.45E+03  3.51E+01  2.49E+03  1.52E+02  0.0141      3.58E+02  3.10E+00  3.61E+02  2.19E+01  0.0086
 1.750      0.422      3.89E+03  6.70E+01  3.95E+03  2.43E+02  0.0169      6.83E+02  6.61E+00  6.90E+02  4.21E+01  0.0096
 2.000      0.451      5.70E+03  1.15E+02  5.81E+03  3.58E+02  0.0199      1.16E+03  1.23E+01  1.17E+03  7.19E+01  0.0105
 2.250      0.480      7.85E+03  1.84E+02  8.04E+03  4.96E+02  0.0229      1.82E+03  2.07E+01  1.84E+03  1.13E+02  0.0113
 2.500      0.507      1.04E+04  2.75E+02  1.06E+04  6.56E+02  0.0259      2.67E+03  3.26E+01  2.71E+03  1.66E+02  0.0120
 2.750      0.533      1.32E+04  3.92E+02  1.36E+04  8.40E+02  0.0288      3.74E+03  4.85E+01  3.79E+03  2.33E+02  0.0128
 3.000      0.559      1.62E+04  5.36E+02  1.68E+04  1.04E+03  0.0319      5.02E+03  6.92E+01  5.09E+03  3.14E+02  0.0136
```

APPENDIX D

Theoretical L-shell ionization and x-ray production cross sections for incident $^{27}_{13}Al^{+}$ ions upon Ni, Cu, Zn, Ge, As, Rb, Sr, Y, Zr, and Pd.

```
          Z1= 18
          A1= 39.9??
          [illegible]          [illegible]          [illegible]          [illegible]

          [illegible]
          [illegible]

J. A. [illegible] (1977): [illegible] 5727.6  [illegible] 5551.7
          [illegible] :          [illegible]  [illegible] 0.4912  [illegible] 0.4681

E. J. MCGUIRE, [illegible] (1972):
SUBSHELL FLUORESCENCE YIELDS
                              [illegible]  [illegible]  [illegible]  [illegible]  [illegible]

COSTER-KRONIG PROBABILITIES     F12    F13    F1?    F23    F2?    F24    F25    F34    F35    F45
                              2.236  2.733  [illegible]  [illegible]  1.110  [illegible]  0.025  [illegible]  0.723  [illegible]

Z1= 18    Z2= 92                        **** K-SHELL CROSS SECTIONS [illegible] ****

                    FIRST [illegible]                                        CROSS  [illegible]
E1(MEV)  KSI RELATIV.  DIRECT + CAPTURE = IONIZATION XRAY PROD.  C/I    DIRECT + CAPTURE = IONIZATION XRAY PROD.  C/I

0.500    0.073     2.65E+00  9.79E-01  3.13E+00  1.83E-01  0.1541    2.95E-35  1.91E-32  2.21E-32  1.28E-33  0.8662
0.750    0.086     1.49E+01  3.29E+00  1.81E+01  1.6?E+00  0.1707    8.33E-19  9.70E-19  1.3?E-18  1.06E-19  0.5235
1.000    0.09?     4.96E+01  1.25E+01  6.21E+01  5.6?E+00  0.2013    3.3?E-12  1.??E-12  4.55E-12  2.77E-13  0.3045
1.250    0.10?     1.2?E+02  3.61E+01  1.61E+02  1.43E+01  0.2251    1.43E-08  3.7?E-09  1.81E-08  1.05E-09  0.2087
1.500    0.11?     2.57E+02  8.62E+01  3.4?E+02  2.02E+01  0.2???    2.71E-06  5.35E-07  3.25E-06  1.86E-07  0.1650
1.750    0.123     4.70E+02  1.8?E+02  6.50E+02  3.6?E+01  0.2763    9.92E-05  1.61E-05  1.15E-04  6.65E-06  0.1421
2.000    0.134     7.??E+02  3.39E+02  1.12E+03  6.6?E+01  0.3010    1.3?E-03  2.??E-04  1.5?E-03  9.32E-05  0.1303
2.250    0.141     1.23E+03  5.91E+02  1.82E+03  1.06E+02  0.3250    1.3?E-02  1.42E-03  1.1?E-02  6.63E-04  0.1237
2.500    0.148     1.81E+03  9.70E+02  2.78E+03  1.65E+02  0.3492    4.86E-02  6.67E-03  5.53E-02  3.20E-03  0.1207
```

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*JULY 1984                                                                              G. LAPICKI   EAST CAROLINA UNIVERSITY
==================================================================================================================================

Z1= 13    Z2= 20                                            **** L-SHELL CROSS SECTIONS (BARN) ****
FLUORESCENCE & COSTER-KRONIG YIELDS FROM KRAUSE [1979]
                                   FIRST BORN APPROXIMATION                                     ECPSSR THEORY
                      -------------------------------------------------------  -------------------------------------------------------
E1(MEV) E1(MEV)/A1(U)  DIRECT + CAPTURE = IONIZATION XRAY PROD.  C/I           DIRECT + CAPTURE = IONIZATION XRAY PROD.  C/I
--------------------------------------------------------------------------------------------------------------------------------

  1.000     0.037     2.37D+05  5.63D+06  5.87D+06  5.39D+04   0.9595     5.59D+01  3.91D+00  5.98D+01  5.49D-01   0.0653
  1.250     0.046     4.26D+05  1.16D+07  1.20D+07  1.10D+05   0.9646     1.40D+02  1.91D+01  1.59D+02  1.46D+00   0.1202
  1.500     0.056     6.66D+05  2.00D+07  2.07D+07  1.90D+05   0.9678     3.02D+02  6.66D+01  3.69D+02  3.38D+00   0.1846
  1.750     0.065     9.53D+05  3.06D+07  3.16D+07  2.90D+05   0.9698     5.96D+02  1.92D+02  7.88D+02  7.23D+00   0.2431
  2.000     0.074     1.29D+06  4.31D+07  4.44D+07  4.07D+05   0.9711     1.11D+03  4.84D+02  1.59D+03  1.46D+01   0.3043
  2.250     0.083     1.66D+06  5.69D+07  5.86D+07  5.37D+05   0.9717     1.96D+03  1.11D+03  3.07D+03  2.81D+01   0.3613
  2.500     0.093     2.07D+06  7.18D+07  7.39D+07  6.77D+05   0.9720     3.35D+03  2.34D+03  5.69D+03  5.22D+01   0.4119


J. A. BEARDEN AND A. F. BURR, REV. MOD. PHYS. 39, 125 (1967):
OBSERVED BINDING ENERGIES (EV): BL1= 1008.1  BL2=  871.9  BL3=  854.7
THETA =4*BL(EV)/Z2L/13.605(EV): TL1= 0.5211  TL2= 0.4507  TL3= 0.4416

W. BAMBYNEK ET AL., REV. MOD. PHYS. 44, 716 (1972):
SUBSHELL FLUORESCENCE YIELDS                  W1          W2          W3
                                          0.0005      0.0000      0.0030
COSTER-KRONIG  PROBABILITIES                 F12         F23         F13
                                           0.325       0.000       0.622

M. O. KRAUSE, J. PHYS. CHEM. REF. DATA 8, 307 (1979):
SUBSHELL FLUORESCENCE YIELDS                  W1          W2          W3
                                          0.0014      0.0036      0.0093
COSTER-KRONIG  PROBABILITIES                 F12         F23         F13
                                           0.300       0.028       0.554

UNOCCUPIED K,L,M,N FRACTIONS FOR  Q =  1.00 : 0.000 0.000 0.689 1.000
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*JULY 1984                                                                         C. CAPICKI  EAST CAROLINA UNIVERSITY
=====================================================================================================================

Z1= 13    Z2= 29                                      **** L-SHELL CROSS SECTIONS (BARN) ****
FLUORESCENCE & COSTER-KRONIG YIELDS FROM KRAUSE (1979)
                                    FIRST BORN APPROXIMATION                                      ECPSSR THEORY
                       --------------------------------------------------------  ---------------------------------------------------
E1(MEV) E1(MEV)/A1(U)  DIRECT + CAPTURE = IONIZATION XRAY PROD.  C/I        DIRECT + CAPTURE = IONIZATION XRAY PROD.  C/I
---------------------------------------------------------------------------------------------------------------------

 1.000    0.037     1.57D+05  2.39D+06  2.54D+06  2.74D+04  0.9383     4.26D+01  2.04D+00  4.46D+01  4.76D-01  0.0466
 1.250    0.046     2.87D+05  5.11D+06  5.40D+06  5.83D+04  0.9469     1.05D+02  1.02D+01  1.15D+02  1.23D+00  0.0880
 1.500    0.056     4.54D+05  9.15D+06  9.60D+06  1.04D+05  0.9527     2.24D+02  3.45D+01  2.59D+02  2.76D+00  0.1336
 1.750    0.065     6.56D+05  1.45D+07  1.51D+07  1.63D+05  0.9566     4.33D+02  9.57D+01  5.29D+02  5.65D+00  0.1808
 2.000    0.074     8.91D+05  2.10D+07  2.19D+07  2.36D+05  0.9593     7.36D+02  2.33D+02  1.02D+03  1.09D+01  0.2283
 2.250    0.083     1.16D+06  2.35D+07  2.97D+07  3.20D+05  0.9611     1.36D+03  5.15D+02  1.86D+03  2.01D+01  0.2745
 2.500    0.093     1.45D+06  3.69D+07  3.83D+07  4.14D+05  0.9622     2.27D+03  1.06D+03  3.33D+03  3.57D+01  0.3179


J. A. BEARDEN AND A. F. BURR, REV. MOD. PHYS. 39, 125 (1967):
OBSERVED BINDING ENERGIES (EV): BL1= 1096.6  BL2=  951.0  BL3=  931.1
THETA =4*BL(EV)/Z2L/13,605(EV): TL1= 0.5221  TL2= 0.4528  TL3= 0.4433

W. BAMBYNEK ET AL., REV. MOD. PHYS. 44, 716 (1972):
SUBSHELL FLUORESCENCE YIELDS                     W1           W2           W3
                                             0.0005       0.0000       0.0094
COSTER-KRONIG  PROBABILITIES                    F12          F23          F13
                                              0.320        0.900        0.623

M. O. KRAUSE, J. PHYS. CHEM. REF. DATA 8, 307 (1979):
SUBSHELL FLUORESCENCE YIELDS                     W1           W2           W3
                                             0.0016       0.0109       0.0110
COSTER-KRONIG  PROBABILITIES                    F12          F23          F13
                                              0.300        0.028        0.510

UNOCCUPIED K,L,M,N FRACTIONS FOR  Q =  1.00 : 0.000 0.000 0.089 1.000
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*JULY 1984                                                                                  G. LAPICKI  EAST CAROLINA UNIVERSITY
==================================================================================================================================

Z1= 13    Z2= 30                                     **** L-SHELL CROSS SECTIONS (BARN) ****

 FLUORESCENCE & COSTER-KRONIG YIELDS FROM KRAUSE [1979]
                                   FIRST BORN APPROXIMATION                                             ECPSSR THEORY
                             ---------------------------------------------------------    ---------------------------------------------------------
 E1(MEV) E1(MEV)/A1(U)   DIRECT + CAPTURE = IONIZATION XRAY PROD.   C/I           DIRECT + CAPTURE = IONIZATION XRAY PROD.   C/I
------------------------------------------------------------------------------------------------------------------------------------------

  1.000       0.037      9.92D+04  9.57D+05  1.06D+06  1.24D+04   0.9061         3.22D+01  1.06D+00  3.33D+01  3.86D-01   0.0324
  1.250       0.046      1.85D+05  2.13D+06  2.31D+06  2.72D+04   0.9200         7.88D+01  5.37D+00  8.42D+01  9.76D-01   0.0638
  1.500       0.056      2.97D+05  3.93D+06  4.23D+06  4.96D+04   0.9297         1.65D+02  1.81D+01  1.83D+02  2.13D+00   0.0985
  1.750       0.065      4.35D+05  6.42D+06  6.86D+06  8.06D+04   0.9365         3.14D+02  4.87D+01  3.63D+02  4.22D+00   0.1343
  2.000       0.074      5.96D+05  9.59D+06  1.02D+07  1.20D+05   0.9415         5.60D+02  1.14D+02  6.74D+02  7.82D+00   0.1702
  2.250       0.083      7.79D+05  1.34D+07  1.42D+07  1.67D+05   0.9450         9.43D+02  2.44D+02  1.19D+03  1.38D+01   0.2058
  2.500       0.093      9.63D+05  1.76D+07  1.86D+07  2.21D+05   0.9476         1.54D+03  4.86D+02  2.02D+03  2.36D+01   0.2494



 J. A. BEARDEN AND A. F. BURR, REV. MOD. PHYS. 39, 125 (1967):
 OBSERVED BINDING ENERGIES (EV): BL1= 1193.6  BL2= 1042.8  BL3= 1019.7
 THETA =4*BL(EV)/Z2L/13.605(EV): TL1= 0.5252  TL2= 0.4568  TL3= 0.4487

 W. BAMBYNEK ET AL., REV. MOD. PHYS. 44, 716 (1972):
                                                  W1           W2           W3
 SUBSHELL FLUORESCENCE YIELDS                 0.0005       0.0000       0.0108
                                                 F12          F23          F13
 COSTER-KRONIG  PROBABILITIES                  0.322        0.000        0.624

 M. O. KRAUSE, J. PHYS. CHEM. REF. DATA 8, 307 (1979):
                                                  W1           W2           W3
 SUBSHELL FLUORESCENCE YIELDS                 0.0016       0.0110       0.0120
                                                 F12          F23          F13
 COSTER-KRONIG  PROBABILITIES                  0.290        0.026        0.340

 UNOCCUPIED K,L,M,N FRACTIONS FOR  I =  1.00 : 0.000 0.000 0.089 1.000
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*JULY 1984                                                                                  G. LAPICKI - EAST CAROLINA UNIVERSITY
=================================================================================================================================

Z1= 13    Z2= 32                                               **** L-SHELL CROSS SECTIONS (BARN) ****

 FLUORESCENCE & COSTER-KRONIG YIELDS FROM KRAUSE (1979)
                                          FIRST BORN APPROXIMATION                                          ECPSSR THEORY
                               -----------------------------------------------------    -----------------------------------------------------
 E1(MEV) E1(MEV)/A1(U)  DIRECT + CAPTURE = IONIZATION XRAY PROD.  C/I       DIRECT + CAPTURE = IONIZATION XRAY PROD.  C/I
---------------------------------------------------------------------------------------------------------------------------------

  1.000       0.037     3.92D+04  1.65D+05  2.04D+05  2.98D+03   0.8090      1.85D+01  3.02D-01  1.88D+01  2.67D-01   0.0161
  1.250       0.046     7.61D+04  3.87D+05  4.63D+05  6.75D+03   0.8355      4.45D+01  1.61D+00  4.61D+01  6.57D-01   0.0349
  1.500       0.056     1.27D+05  7.54D+05  8.80D+05  1.28D+04   0.8562      9.15D+01  5.49D+00  9.70D+01  1.38D+00   0.0566
  1.750       0.065     1.90D+05  1.29D+06  1.48D+06  2.17D+04   0.8720      1.69D+02  1.45D+01  1.84D+02  2.63D+00   0.0791
  2.000       0.074     2.60D+05  2.03D+06  2.29D+06  3.35D+04   0.8840      2.92D+02  3.29D+01  3.25D+02  4.65D+00   0.1014
  2.250       0.083     3.54D+05  2.96D+06  3.32D+06  4.84D+04   0.8934      4.77D+02  6.71D+01  5.44D+02  7.80D+00   0.1234
  2.500       0.093     4.52D+05  4.10D+06  4.55D+06  6.65D+04   0.9006      7.48D+02  1.27D+02  8.75D+02  1.26D+01   0.1449


 J. A. BEARDEN AND A. F. BURR, REV. MOD. PHYS. 39, 125 (1967):
 OBSERVED BINDING ENERGIES (EV): BL1= 1414.3  BL2= 1247.6  BL3= 1216.7
 THETA =4*BL(EV)/Z2L/13.605(EV): TL1= 0.5361  TL2= 0.4730  TL3= 0.4612

 W. BAMBYNEK ET AL., REV. MOD. PHYS. 44, 716 (1972):
 SUBSHELL FLUORESCENCE YIELDS                  W1           W2           W3
                                            0.0005       0.0000       0.0144
 COSTER-KRONIG  PROBABILITIES                  F12          F23          F13
                                             0.266        0.000        0.671

 M. O. KRAUSE, J. PHYS. CHEM. REF. DATA 8, 307 (1979):
 SUBSHELL FLUORESCENCE YIELDS                  W1           W2           W3
                                            0.0024       0.0139       0.0130
 COSTER-KRONIG  PROBABILITIES                  F12          F23          F13
                                             0.289        0.950        0.530

 UNOCCUPIED K,L1,L2,L3 FRACTIONS FOR  Q =  1.00 : 0.000 0.000 0.889 1.000
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*JULY 1984                                                                         G. LAPICKI, EAST CAROLINA UNIVERSITY
=========================================================================================================================

Z1= 13     Z2= 33                                  **** L-SHELL CROSS SECTIONS (BARN) ****

 FLUORESCENCE & COSTER-KRONIG YIELDS FROM KRAUSE [1979]
                                   FIRST BORN APPROXIMATION                                     ECPSSR THEORY
                        ---------------------------------------------------------------------------------------------------------
 E1(MEV) E1(MEV)/A1(U)  DIRECT + CAPTURE = IONIZATION XRAY PROD.   C/I          DIRECT + CAPTURE = IONIZATION XRAY PROD.   C/I
 ------------------------------------------------------------------------------------------------------------------------

  1.000        0.037       2.510+04  7.360+04  9.870+04  1.550+03   0.7458       1.640+01  1.640-01  1.650+01  2.250-01   0.0113
  1.250        0.046       4.950+04  1.750+05  2.250+05  3.520+03   0.7797       3.440+01  9.160-01  3.530+01  5.480-01   0.0260
  1.500        0.056       8.350+04  3.470+05  4.310+05  6.760+03   0.8062       7.020+01  3.200+00  7.340+01  1.140+00   0.0436
  1.750        0.065       1.270+05  6.070+05  7.340+05  1.150+04   0.8270       1.290+02  8.540+00  1.380+02  2.130+00   0.0621
  2.000        0.074       1.790+05  9.670+05  1.150+06  1.800+04   0.8435       2.200+02  1.930+01  2.390+02  3.710+00   0.0806
  2.250        0.083       2.410+05  1.440+06  1.680+06  2.630+04   0.8566       3.540+02  3.880+01  3.930+02  6.110+00   0.0987
  2.500        0.093       3.100+05  2.020+06  2.330+06  3.660+04   0.8671       5.530+02  7.210+01  6.250+02  9.650+00   0.1163


 J. A. BEARDEN AND A. F. BURR, REV. MOD. PHYS. 39, 125 (1967):
 OBSERVED BINDING ENERGIES (EV): BL1= 1526.5  BL2= 1359.6  BL3= 1323.1
 THETA =4*BL(EV)/Z2L/13.605(EV): TL1= 0.5392  TL2= 0.4799  TL3= 0.4674

 W. BAMBYNEK ET AL., REV. MOD. PHYS. 44, 716 (1972):
 SUBSHELL FLUORESCENCE YIELDS                  W1         W2         W3
                                             0.0019     0.0066     0.0161
 COSTER-KRONIG  PROBABILITIES                  F12        F23        F13
                                              0.284      0.000      0.594

 M. O. KRAUSE, J. PHYS. CHEM. REF. DATA 8, 307 (1979):
 SUBSHELL FLUORESCENCE YIELDS                  W1         W2         W3
                                             0.0023     0.0146     0.0150
 COSTER-KRONIG  PROBABILITIES                  F12        F23        F13
                                              0.280      0.063      0.550

 UNOCCUPIED K,L,M FRACTIONS FOR  J =  1.00 : 0.000 0.000 0.000 1.000
```

```
=====================================================================================================================================
Z1= 13     Z2= 37                                          ****  L-SHELL CROSS SECTIONS (BARN) ****

FLUORESCENCE & COSTER-KRONIG YIELDS FROM KRAUSE (1979)
---------------------------------------------------------------------------------------------------------------------------------------
                                       FIRST BORN APPROXIMATION                                              ECPSSR THEORY
                            --------------------------------------------------------------------------------------------------------
E1(MEV) E1(MEV)/A1(U)  DIRECT + CAPTURE = IONIZATION XRAY PROD.   C/T           DIRECT + CAPTURE = IONIZATION XRAY PROD.   C/T
---------------------------------------------------------------------------------------------------------------------------------------
 1.000      0.037      4.400D+03  3.880D+03  8.280D+03  1.990D+02   0.4691      5.270D+00  1.320D-02  5.290D+00  1.260D-01   0.0025
 1.250      0.046      9.250D+03  9.630D+03  1.890D+04  4.540D+02   0.5101      1.240D+01  9.540D-02  1.250D+01  2.980D-01   0.0076
 1.500      0.056      1.650D+04  2.000D+04  3.650D+04  8.760D+02   0.5475      2.500D+01  3.830D-01  2.540D+01  6.040D-01   0.0151
 1.750      0.065      2.630D+04  3.650D+04  6.280D+04  1.510D+03   0.5812      4.510D+01  1.100D+00  4.620D+01  1.100D+00   0.0238
 2.000      0.074      3.880D+04  6.100D+04  9.980D+04  2.400D+03   0.6113      7.510D+01  2.570D+00  7.760D+01  1.850D+00   0.0332
 2.250      0.083      5.390D+04  9.500D+04  1.490D+05  3.590D+03   0.6381      1.180D+02  5.240D+00  1.230D+02  2.930D+00   0.0425
 2.500      0.093      7.160D+04  1.400D+05  2.120D+05  5.100D+03   0.6617      1.770D+02  9.650D+00  1.860D+02  4.440D+00   0.0518


---------------------------------------------------------------------------------------------------------------------------------------
J. A. BEARDEN AND A. F. BURR, REV. MOD. PHYS. 39, 125 (1967):
---------------------------------------------------------------------------------------------------------------------------------------
OBSERVED BINDING ENERGIES (EV): BL1= 2065.1   BL2= 1863.9   BL3= 1804.4
THETA =4*BL(EV)/Z2L/13.605(EV): TL1= 0.5626   TL2= 0.5078   TL3= 0.4916
---------------------------------------------------------------------------------------------------------------------------------------

W. BAMBYNEK ET AL., REV. MOD. PHYS. 44, 716 (1972):
---------------------------------------------------------------------------------------------------------------------------------------
SUBSHELL FLUORESCENCE YIELDS                             W1           W2           W3
                                                       0.0024       0.0222       0.0240
COSTER-KRONIG  PROBABILITIES                             F12          F23          F13
                                                        0.240        0.192        0.455
---------------------------------------------------------------------------------------------------------------------------------------

M. O. KRAUSE, J. PHYS. CHEM. REF. DATA 8, 307 (1979):
---------------------------------------------------------------------------------------------------------------------------------------
SUBSHELL FLUORESCENCE YIELDS                             W1           W2           W3
                                                       0.0046       0.0223       0.0240
COSTER-KRONIG  PROBABILITIES                             F12          F23          F13
                                                        0.271        0.109        0.520
---------------------------------------------------------------------------------------------------------------------------------------

UNOCCUPIED K,L,M,N FRACTIONS FOR  Q =  1.00 : 0.000 0.000 0.849 1.000
---------------------------------------------------------------------------------------------------------------------------------------
```

```
*JULY 1984                                                                                          G. LAPICKI  EAST CAROLINA UNIVERSITY
===============================================================================================================================
Z1= 13    Z2= 38                                      ****  L-SHELL CROSS SECTIONS (BARN) ****
 FLUORESCENCE & COSTER-KRONIG YIELDS FROM KRAUSE (1979)
                                     FIRST BORN APPROXIMATION                                                     ECPSSR THEORY
                                    ---------------------------------------------------------------------------------------------------------
 E1(MEV) E1(MEV)/A1(U)  DIRECT + CAPTURE = IONIZATION XRAY PROD.   C/I             DIRECT + CAPTURE = IONIZATION XRAY PROD.   C/I
-------------------------------------------------------------------------------------------------------------------------------
   1.000       0.037     2.69D+03  1.99D+03  4.68D+03  1.28D+02   0.4263            4.17D+00  6.94D-03  4.17D+00  1.08D-01   0.0017
   1.250       0.046     6.16D+03  4.96D+03  1.11D+04  2.91D+02   0.4464            9.79D+00  5.43D-02  9.85D+00  2.56D-01   0.0055
   1.500       0.055     1.11D+04  1.03D+04  2.15D+04  5.62D+02   0.4822            1.96D+01  2.28D-01  1.99D+01  5.16D-01   0.0115
   1.750       0.065     1.79D+04  1.91D+04  3.70D+04  7.69D+02   0.5159            3.55D+01  6.73D-01  3.62D+01  9.34D-01   0.0187
   2.000       0.074     2.67D+04  3.21D+04  5.88D+04  1.54D+03   0.5460            5.86D+01  1.60D+00  6.02D+01  1.56D+00   0.0266
   2.250       0.083     3.74D+04  5.03D+04  8.77D+04  2.30D+03   0.5738            9.16D+01  3.29D+00  9.49D+01  2.47D+00   0.0347
   2.500       0.093     5.01D+04  7.47D+04  1.25D+05  3.27D+03   0.5949            1.37D+02  6.10D+00  1.43D+02  3.72D+00   0.0427


 J. A. BEARDEN AND A. F. BURR, REV. MOD. PHYS. 39, 125 (1967):
 OBSERVED BINDING ENERGIES (EV): BL1= 2216.3  BL2= 2006.8  BL3= 1939.6
 THETA =4*BL(EV)/Z2L/13.605(EV): TL1= 0.5687  TL2= 0.5149  TL3= 0.4977

 W. BAMBYNEK ET AL., REV. MOD. PHYS. 44, 716 (1972):
 SUBSHELL FLUORESCENCE YIELDS                     W1          W2          W3
                                               0.0030      0.0224      0.0243
 COSTER-KRONIG  PROBABILITIES                     F12         F23         F13
                                                0.249       0.115       0.640

 M. O. KRAUSE, J. PHYS. CHEM. REF. DATA 8, 307 (1979):
 SUBSHELL FLUORESCENCE YIELDS                     W1          W2          W3
                                               0.0051      0.0240      0.0260
 COSTER-KRONIG  PROBABILITIES                     F12         F23         F13
                                                0.270       0.117       0.520

 UNOCCUPIED K,L,M FRACTIONS FOR  X =  1.00 : 0.000 0.100 0.889 1.000
```

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*JULY 1984                                                                                  G. LAPICKI, EAST CAROLINA UNIVERSITY
==================================================================================================================================

Z1= 13    Z2= 39                                   **** L-SHELL CROSS SECTIONS (BARN) ****

FLUORESCENCE & COSTER-KRONIG YIELDS FROM KRAUSE (1979)
                                 FIRST BORN APPROXIMATION                                       ECPSSR THEORY
                          ==================================================================================================
E1(MEV) E1(MEV)/A1(U)   DIRECT + CAPTURE = IONIZATION X-RAY PROD.   C/I        DIRECT + CAPTURE = IONIZATION X-RAY PROD.   C/I
====================================================================================================================================

 1.000      0.037       1.920+03  1.050+03  2.970+03  8.410+01    0.3536       3.320+00  3.620-03  3.320+00  9.360-02    0.0011
 1.250      0.046       4.140+03  2.630+03  6.770+03  1.920+02    0.3889       7.780+00  3.080-02  7.810+00  2.200-01    0.0039
 1.500      0.056       7.550+03  5.520+03  1.310+04  3.700+02    0.4221       1.550+01  1.360-01  1.570+01  4.420-01    0.0086
 1.750      0.065       1.230+04  1.020+04  2.250+04  6.350+02    0.4536       2.790+01  4.140-01  2.830+01  7.970-01    0.0146
 2.000      0.074       1.850+04  1.730+04  3.580+04  1.010+03    0.4833       4.610+01  1.000+00  4.710+01  1.330+00    0.0213
 2.250      0.083       2.610+04  2.730+04  5.340+04  1.510+03    0.5112       7.190+01  2.090+00  7.400+01  2.090+00    0.0282
 2.500      0.093       3.520+04  4.080+04  7.600+04  2.150+03    0.5365       1.070+02  3.900+00  1.110+02  3.130+00    0.0352


J. A. BEARDEN AND A. F. BURR, REV. MOD. PHYS. 39, 125 (1967):
OBSERVED BINDING ENERGIES (EV): BL1= 2372.5  BL2= 2155.5  BL3= 2080.0
THETA =4*BL(EV)/Z2L/13.605(EV): TL1= 0.5743  TL2= 0.5218  TL3= 0.5035

W. BAMBYNEK ET AL., REV. MOD. PHYS. 44, 716 (1972):
SUBSHELL FLUORESCENCE YIELDS                   W1          W2          W3
                                           0.0035      0.0259      0.0269
COSTER-KRONIG  PROBABILITIES                  F12         F23         F13
                                            0.242       0.116       0.647

M. O. KRAUSE, J. PHYS. CHEM. REF. DATA 8, 307 (1979):
SUBSHELL FLUORESCENCE YIELDS                   W1          W2          W3
                                           0.0059      0.0260      0.0263
COSTER-KRONIG  PROBABILITIES                  F12         F23         F13
                                            0.260       0.125       0.520

J?CCO?IL? K,L,M,N FRACTIONS FOR ? =  1.00 : 0.00? 0.0?6 0.?89 1.000
```

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*JULY 1984                                                                             G. LAPICKI   EAST CAROLINA UNIVERSITY
==============================================================================================================================

Z1= 13    Z2= 40                                        **** L-SHELL CROSS SECTIONS (BARN) ****
 FLUORESCENCE & COSTER-KRONIG YIELDS FROM KRAUSE (1979)
                                     FIRST BORN APPROXIMATION                                           ECPSSR-THEORY
                          ------------------------------------------------------------------------------------------------
 E1(MEV) E1(MEV)/A1(U)  DIRECT + CAPTURE = IONIZATION XRAY PROD.  C/I        DIRECT + CAPTURE = IONIZATION XRAY PROD.  C/I
------------------------------------------------------------------------------------------------------------------------------

  1.000      0.037      1.300+03  5.920+02  1.830+03  5.890+01  0.3088      2.680+00  1.920-03  2.680+00  8.370-02  0.0007
  1.250      0.046      2.840+03  1.460+03  4.290+03  1.340+02  0.3392      6.250+00  1.760-02  6.270+00  1.960-01  0.0028
  1.500      0.056      5.230+03  3.060+03  8.290+03  2.530+02  0.3691      1.250+01  8.230-02  1.250+01  3.920-01  0.0066
  1.750      0.065      8.600+03  5.690+03  1.430+04  4.470+02  0.3962      2.230+01  2.590-01  2.250+01  7.050-01  0.0115
  2.000      0.074      1.300+04  9.670+03  2.270+04  7.100+02  0.4262      3.680+01  6.410-01  3.740+01  1.170+00  0.0171
  2.250      0.083      1.850+04  1.530+04  3.390+04  1.060+03  0.4528      5.720+01  1.350+00  5.850+01  1.830+00  0.0231
  2.500      0.093      2.520+04  2.300+04  4.820+04  1.510+03  0.4779      8.530+01  2.555+00  8.790+01  2.740+00  0.0292


 J. A. BEARDEN AND A. F. BURR, REV. MOD. PHYS. 39, 125 (1967):
 OBSERVED BINDING ENERGIES (EV): BL1= 2531.6  BL2= 2306.7  BL3= 2222.3
 THETA =4*BL(EV)/Z2L/13.605(EV): TL1= 0.5791  TL2= 0.5277  TL3= 0.5084

 W. BAMBYNEK ET AL., REV. MOD. PHYS. 44, 716 (1972):
 SUBSHELL FLUORESCENCE YIELDS                      W1          W2          W3
                                               0.0040      0.0294      0.0295
 COSTER-KRONIG  PROBABILITIES                     F12         F23         F13
                                                0.236       0.118       0.645

 M. O. KRAUSE, J. PHYS. CHEM. REF. DATA 8, 307 (1979):
 SUBSHELL FLUORESCENCE YIELDS                      W1          W2          W3
                                               0.0068      0.0280      0.0319
 COSTER-KRONIG  PROBABILITIES                     F12         F23         F13
                                                0.260       0.132       0.520

 UNOCCUPIED K,L,M FRACTIONS FOR Z = 1.00 : 0.000 0.000 0.089 1.000
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```
*JULY 1984                                                                                            G. LAPICKI  EAST CAROLINA UNIVERSITY
==========================================================================================================================================

Z1= 13     Z2= 46                                               ****  L-SHELL CROSS SECTIONS (BARN) ****
 FLUORESCENCE & COSTER-KRONIG YIELDS FROM KRAUSE [1979]
                                               FIRST BORN APPROXIMATION                                            ECPSSR THEORY
                               ----------------------------------------------------------------------------------------------------------
 E1(MEV) E1(MEV)/M1(U)  DIRECT + CAPTURE = IONIZATION XRAY PROD.  C/I         DIRECT + CAPTURE = IONIZATION XRAY PROD.  C/I
------------------------------------------------------------------------------------------------------------------------------------------

   1.000        0.037      1.54D+02  2.55D+01  1.79D+02  8.86D+00   0.1420       8.44D-01  3.96D-05  8.44D-01  4.13D-02   0.0000
   1.250        0.046      3.51D+02  6.40D+01  4.15D+02  2.06D+01   0.1543       1.92D+00  6.55D-04  1.92D+00  9.40D-02   0.0003
   1.500        0.056      6.76D+02  1.36D+02  8.12D+02  4.03D+01   0.1671       3.76D+00  4.28D-03  3.76D+00  1.84D-01   0.0011
   1.750        0.065      1.16D+03  2.55D+02  1.42D+03  7.06D+01   0.1804       6.63D+00  1.66D-02  6.65D+00  3.26D-01   0.0025
   2.000        0.074      1.83D+03  4.40D+02  2.27D+03  1.13D+02   0.1949       1.09D+01  4.85D-02  1.09D+01  5.34D-01   0.0045
   2.250        0.083      2.71D+03  7.10D+02  3.42D+03  1.70D+02   0.2077       1.67D+01  1.14D-01  1.68D+01  8.24D-01   0.0068
   2.500        0.093      3.31D+03  1.09D+03  4.39D+03  2.44D+02   0.2220       2.45D+01  2.32D-01  2.47D+01  1.21D+00   0.0094


 J. A. BEARDEN AND A. F. BURR, REV. MOD. PHYS. 39, 125 (1967):
 OBSERVED BINDING ENERGIES (EV): BL1= 3604.3  BL2= 3330.3  BL3= 3173.3
 THETA =4*BL(EV)/Z2L/13.605(EV): TL1= 0.6051  TL2= 0.5591  TL3= 0.5327

 W. BAMBYNEK ET AL., REV. MOD. PHYS. 44, 716 (1972):
 SUBSHELL FLUORESCENCE YIELDS                     L1            L2            L3
                                              0.0094        0.0504        0.0551
 COSTER-KRONIG  PROBABILITIES                    F12           F23           F13
                                               0.059         0.147         0.784

 M. O. KRAUSE, J. PHYS. CHEM. REF. DATA 8, 307 (1979):
 SUBSHELL FLUORESCENCE YIELDS                     L1            L2            L3
                                              0.0140        0.0473        0.0490
 COSTER-KRONIG  PROBABILITIES                    F12           F23           F13
                                               0.100         0.151         0.600

 UNOCCUPIED K,L,M FRACTIONS FOR I =  1.00 : 0.000  .100 0.589 1.000
```

APPENDIX E

Theoretical M-shell ionization and x-ray production cross sections for incident $^{27}_{13}\mathrm{Al}^{+}$ ions upon Pr, Nd, Eu, Gd, Dy, Ho, Er, Yb, Lu, Hf, Au, Pb, Bi, and U.

```
              Z1= 13.
              M1= 26.980
              VEL=    0.59600        VMAX=    0.52000        VTOT=    0.25500

              Z2= 59
              M2= 140.907

 J. A. BEARDEN AND A. F. BURR, REV. MOD. PHYS. 39, 125 (1967): M1= 1511.0  M2= 1337.4  M3= 1242.2  M4=  951.1  M5=  931.0
              THETA = 9 * BI(EV) / Z2**2 /13.605(EV) :        TH1= 0.4384  TH2= 0.3860  TH3= 0.3604  TH4= 0.4392  TH5= 0.4299

 E. J. MCGUIRE, PHYS. REV. A5, 1043 (1972):
 SUBSHELL FLUORESCENCE YIELDS
                                              1            2            3            4            5
                                        0.000520     0.001250     0.002103     0.002600     0.002533

 COSTER-KRONIG PROBABILITIES           S12    S13    S14    S15    S23    S24    S25    S34    S35    S45
                                     0.222  0.495  0.002  0.132  0.049  0.615  0.209  0.182  0.701  0.233

 Z1= 13     Z2= 59                                  **** M-SHELL CROSS SECTIONS (BARN) ****

                          FIRST BORN APPROXIMATION                                              ECPSS  THEORY
                   ---------------------------------------------------------------------------------------------------------------------
 E1(MEV)  KSI RELATIV.  DIRECT + CAPTURE = IONIZATION XRAY PROD.  C/I            DIRECT + CAPTURE = IONIZATION XRAY PROD.   C/I
 ---------------------------------------------------------------------------------------------------------------------------------------

  0.500      0.126     2.56E+04  2.89E+05  3.14E+05  8.13E+02  0.9185        4.24E-03  7.91E-03  1.21E-02  3.07E-05   0.6510
  0.750      0.154     1.05E+05  1.79E+06  1.89E+06  4.89E+03  0.9444        2.53E+00  3.24E+00  5.77E+00  1.49E-02   0.5618
  1.000      0.179     2.49E+05  5.83E+06  6.10E+06  1.58E+04  0.9559        5.67E+01  7.45E+01  1.31E+02  3.40E-01   0.5681
  1.250      0.202     5.32E+05  1.35E+07  1.40E+07  3.62E+04  0.9620        3.69E+02  5.60E+02  9.28E+02  2.41E+00   0.6029
  1.500      0.224     8.96E+05  2.51E+07  2.60E+07  6.74E+04  0.9656        1.29E+03  2.37E+03  3.66E+03  9.52E+00   0.6481
  1.750      0.246     1.35E+06  4.06E+07  4.20E+07  1.09E+05  0.9679        3.17E+03  7.14E+03  1.03E+04  2.68E+01   0.6925
  2.000      0.267     1.90E+06  5.94E+07  6.13E+07  1.59E+05  0.9690        6.28E+03  1.71E+04  2.34E+04  6.09E+01   0.7317
  2.250      0.289     2.48E+06  8.06E+07  8.31E+07  2.16E+05  0.9702        1.06E+04  3.49E+04  4.56E+04  1.19E+02   0.7631
  2.500      0.310     3.10E+06  1.03E+08  1.07E+08  2.77E+05  0.9709        1.71E+04  6.31E+04  6.02E+04  2.09E+02   0.7862
```

```
Z1= 13
A1= 26.980
[illegible]= 0.36[illegible]      [illegible]X=     [illegible]      [illegible]=    0.2[illegible]

Z2= 5[illegible]
A2= 1[illegible].2[illegible]

J. A. BEARDEN AND A. F. BURR, REV. MOD. PHYS. 39, 125 (1967): [illegible] 1= 1[illegible]  [illegible] 2= 14[illegible]  [illegible] 3= 12[illegible]  [illegible] 4= [illegible]  [illegible] 5= [illegible]
              THETA = 4 * [illegible](Z?) / Z2 /13.6[illegible] :        T 1= [illegible]  T 2= [illegible]  T 3= [illegible]  T 4= 0.4332  T 5= 0.4285

E. J. MCGUIRE, PHYS. REV. A5, 1043 (1972):
SUBSHELL FLUORESCENCE YIELDS                     1              2              3              4              5
                                            [illegible]     0.00132     0.01[illegible]     [illegible]     [illegible]

COSTER-KRONIG PROBABILITIES        S12    S13    S14    S15    S23    S24    S25    S34    S35    S45
                                 0.236  0.469  0.092  0.125  0.957  0.649  0.172  0.171  0.712  0.267

Z1= 13     Z2= 5[illegible]                              ****  M-SHELL CROSS SECTIONS ([illegible])  ****

                          FIRST BORN APPROXIMATION                                                  ECPSSR THEORY
           -----------------------------------------------------------------------------------------------------------------------
E1(MEV)  KSI RELATIV.  DIRECT + CAPTURE = IONIZATION XRAY PROD.   C/I          DIRECT + CAPTURE = IONIZATION XRAY PROD.   C/I
-------------------------------------------------------------------------------------------------------------------------------

 0.500      0.125      1.97E+04  1.67E+05  1.87E+05  5.51E+02   0.8946        2.19E-03  3.63E-03  5.82E-03  2.33E-05   0.6252
 0.750      0.152      8.15E+04  1.06E+06  1.14E+06  5.90E+03   0.9256        1.61E+00  1.82E+00  3.43E+00  1.38E-02   0.5309
 1.000      0.177      2.10E+05  3.55E+06  3.76E+06  1.27E+04   0.9442        3.56E+01  4.53E+01  8.09E+01  3.41E-01   0.5333
 1.250      0.200      4.19E+05  6.42E+06  6.84E+06  2.97E+04   0.9526        2.72E+02  3.55E+02  6.27E+02  2.51E+00   0.5665
 1.500      0.221      7.12E+05  1.61E+07  1.68E+07  3.62E+04   0.9576        9.81E+02  1.55E+03  2.53E+03  1.01E+01   0.6121
 1.750      0.243      1.05E+06  2.66E+07  2.77E+07  9.23E+04   0.9609        2.48E+03  4.75E+03  7.23E+03  2.89E+01   0.6575
 2.000      0.263      1.53E+06  3.97E+07  4.12E+07  1.37E+05   0.9627        4.99E+03  1.1[illegible]E+04  1.66E+04  6.60E+01   0.6991
 2.250      0.284      2.13E+06  5.49E+07  5.70E+07  1.89E+05   0.9644        9.71E+03  2.40E+04  3.37E+04  1.30E+02   0.7336
 2.500      0.304      2.54E+06  7.18E+07  7.43E+07  2.46E+05   0.9659        1.30E+04  4.39E+04  5.77E+04  2.28E+02   0.7601
```

```
Z1= 13.
A1= 26.980
EMIN=    0.50000        EMAX=    2.50000        ESTEP=    0.25000

Z2= 63
A2= 152.0

J. A. BEARDEN AND A. F. BURR, REV. MOD. PHYS. 39, 125 (1967): EM1= 1800.  EM2= 1614.  EM3= 1481.  EM4= 1160.6  EM5= 1130.9
            THETA = 9 * M (27) / 729 /13.605(EM) :        TM1= 0.6046  TM2= 0.5967  TM3= 0.5857  TM4= 0.4504  TM5= 0.4271

E. J. MCGUIRE, PHYS. REV. A5, 1043 (1972):
SUBSHELL FLUORESCENCE YIELDS               W1          W2          W3          W4          W5
                                    0.00072     0.01475     0.01065     0.00420     0.00596

COSTER-KRONIG PROBABILITIES        S12   S13   S14   S15   S23   S24   S25   S34   S35   S45
                                  0.330 0.465 0.070 0.100 0.062 0.511 0.137  .161 0.726 0.363

Z1= 13     Z2= 63                          **** M-SHELL CROSS SECTIONS (BARN) ****

                     FIRST BORN APPROXIMATION                                              ECPSSR THEORY
                   ---------------------------------------------------------------------------------------------------
E1(MEV)  KSI RELATIV.  DIRECT + CAPTURE = IONIZATION XRAY PROD.  C/I        DIRECT + CAPTURE = IONIZATION XRAY PROD.  C/I
-------------------------------------------------------------------------------------------------------------------------

 0.500       0.122      8.61E+03  3.14E+04  4.02E+04  2.56E+02   0.7809     2.57E-04  2.87E-04  5.44E-04  3.54E-06   0.5288
 0.750       0.149      3.73E+04  2.10E+05  2.47E+05  1.52E+03   0.8509     3.75E-01  2.75E-01  6.50E-01  4.23E-03   0.4227
 1.000       0.172      9.95E+04  7.48E+05  8.47E+05  5.16E+03   0.8837     1.26E+01  8.92E+00  2.15E+01  1.40E-01   0.4149
 1.250       0.193      2.02E+05  1.89E+06  2.09E+06  1.27E+04   0.9036     1.02E+02  8.07E+01  1.83E+02  1.19E+00   0.4412
 1.500       0.213      3.50E+05  3.84E+06  4.19E+06  2.55E+04   0.9166     4.15E+02  3.85E+02  8.00E+02  5.17E+00   0.4812
 1.750       0.233      5.46E+05  6.73E+06  7.28E+06  4.42E+04   0.9250     1.13E+03  1.26E+03  2.40E+03  1.55E+01   0.5264
 2.000       0.252      7.84E+05  1.06E+07  1.14E+07  6.91E+04   0.9313     2.42E+03  3.24E+03  5.66E+03  3.65E+01   0.5718
 2.250       0.271      1.07E+06  1.55E+07  1.65E+07  1.00E+05   0.9356     4.41E+03  6.99E+03  1.14E+04  7.33E+01   0.6135
 2.500       0.289      1.35E+06  2.12E+07  2.26E+07  1.37E+05   0.9368     7.19E+03  1.33E+04  2.05E+04  1.32E+02   0.6494
```

```
        Z1= 13
        M1= 26.980
        [illegible]

        Z2= 64
        M2= 157.250

J. A. BEARDEN AND A. F. BURR, REV. MOD. PHYS. 39, 125 (1967): M1= 1881.  M2= 1688.  M3= 1544.  M4= 1217.2  M5= 1185.2
        THETA = 2 * EI(EV) / Z2**2 /13.605(EV) :      TM1= 0.4471  TM2= 0.4117  TM3= 0.3671  TM4= 0.4385  TM5= 0.4270

E. J. MCGUIRE, PHYS. REV. A 5, 1043 (1972):
M-SHELL FLUORESCENCE YIELDS
                                  1            2            3            4            5
                           0.[illegible]  0.[illegible]157  0.[illegible]131  0.[illegible]725  0.[illegible]171[illegible]

COSTER-KRONIG PROBABILITIES     S12   S13   S14   S15   S23   S24   S25   S34   S35   F45
                               0.323 0.004 0.063 0.0[illegible] 0.073 0.552 0.133 0.160 0.726 0.379

Z1= 13    Z2= 64                         **** M-SHELL CROSS SECTIONS (BARN) ****

                         FIRST BORN APPROXIMATION                                     ECPSSR THEORY
EI(MEV)  KSI RELATIV.  DIRECT + CAPTURE = IONIZATION XRAY PROD.  C/I       DIRECT + CAPTURE = IONIZATION XRAY PROD.  C/I

 0.500     0.121       6.80E+03  1.87E+04  2.55E+04  1.89E+02  0.7356     1.27E-04  1.26E-04  2.53E-04  1.94E-06  0.4999
 0.750     0.147       2.90E+04  1.26E+05  1.55E+05  1.14E+03  0.8132     2.34E-01  1.50E-01  3.84E-01  2.94E-03  0.3909
 1.000     0.170       7.71E+04  4.57E+05  5.34E+05  3.91E+03  0.8557     8.72E+00  5.34E+00  1.41E+01  1.08E-01  0.3797
 1.250     0.191       1.59E+05  1.17E+06  1.33E+06  9.70E+03  0.8810     7.47E+01  5.05E+01  1.25E+02  9.56E-01  0.4035
 1.500     0.211       2.70E+05  2.42E+06  2.70E+06  1.96E+04  0.8972     3.14E+02  2.46E+02  5.61E+02  4.28E+00  0.4415
 1.750     0.230       4.36E+05  4.32E+06  4.75E+06  3.45E+04  0.9083     8.80E+02  8.29E+02  1.71E+03  1.30E+01  0.4850
 2.000     0.248       6.30E+05  6.91E+06  7.54E+06  5.47E+04  0.9165     1.92E+03  2.14E+03  4.06E+03  3.11E+01  0.5298
 2.250     0.267       8.56E+05  1.02E+07  1.11E+07  8.05E+04  0.9226     3.53E+03  4.73E+03  8.27E+03  6.29E+01  0.5726
 2.500     0.285       1.13E+06  1.42E+07  1.53E+07  1.11E+05  0.9265     5.82E+03  9.12E+03  1.49E+04  1.13E+02  0.6103
```

```
Z1= 13
A1= 26.980
E1= 0.50000        [illegible]= 2.50000        [illegible]= 0.25000

Z2= 66
A2= 162.50

J. A. BEARDEN AND A. F. BURR, REV. MOD. PHYS. 39, 125 (1967): U1= 2046.8  U2= 1841.8  U3= 1675.6  U4= 1332.5  U5= 1294.9
            THET. = 4 * U(Z2) / Z2** /13.605(Z1) :        TH1= 0.6517  TH2= [illegible]  TH3= [illegible]  TH4= 0.4362  TH5= 0.4255

E. J. MCGUIRE, PHYS. REV. A5, 1043 (1972):
SUBSHELL FLUORESCENCE YIELDS                 1           2           3           4           5
                                       0.001153    0.001763    0.001600    [illegible] [illegible]

COSTER-KRONIG PROBABILITIES        S12   S13   S14   S15   S23   S24   S25   S34   S35   F45
                                 0.234 0.513 0.043 0.133 0.095 0.520 0.121 0.151 0.743 0.398

Z1= 13     Z2= 66                      **** M-SHELL CROSS SECTIONS ([illegible]) ****

                          FIRST BORN APPROXIMATION                                   ECPSSR THEORY
                  ----------------------------------------------------------------------------------------------------
E1(MEV)  KST RELATIV.  DIRECT + CAPTURE = IONIZATION XRAY PROD.   C/I       DIRECT + CAPTURE = IONIZATION XRAY PROD.   C/I
---------------------------------------------------------------------------------------------------------------------------

 0.500      0.110     4.14E+03 7.16E+03 1.13E+04 1.11E+02   0.6343      2.83E-05 2.28E-05 5.11E-05 5.07E-07   0.4461
 0.750      0.145     1.80E+04 4.92E+04 6.72E+04 6.51E+02   0.7326      8.66E-02 4.39E-02 1.31E-01 1.30E-03   0.3353
 1.000      0.167     4.64E+04 1.84E+05 2.31E+05 2.23E+03   0.7962      4.00E+00 1.92E+00 5.92E+00 5.96E-02   0.3240
 1.250      0.187     1.01E+05 4.80E+05 5.81E+05 5.59E+03   0.8262      3.90E+01 1.99E+01 5.89E+01 5.87E-01   0.3376
 1.500      0.206     1.79E+05 1.02E+06 1.20E+06 1.15E+04   0.8509      1.78E+02 1.04E+02 2.82E+02 2.81E+00   0.3687
 1.750      0.225     2.83E+05 1.87E+06 2.15E+06 2.06E+04   0.8681      5.25E+02 3.63E+02 8.88E+02 8.84E+00   0.4090
 2.000      0.242     4.15E+05 3.07E+06 3.48E+06 3.33E+04   0.8808      1.19E+03 9.79E+02 2.17E+03 2.16E+01   0.4510
 2.250      0.260     5.71E+05 4.64E+06 5.22E+06 4.99E+04   0.8905      2.27E+03 2.20E+03 4.47E+03 4.44E+01   0.4926
 2.500      0.277     7.55E+05 6.61E+06 7.36E+06 7.04E+04   0.8977      3.82E+03 4.34E+03 8.16E+03 8.11E+01   0.5321
```

```
Z1= 13
M1= 26.9[illegible]
[illegible]=   [illegible]          [illegible]=   [illegible]          [illegible]=   0.25[illegible]

Z2= 67
M2= 1[illegible]

J. [illegible]: [illegible]= [illegible]  [illegible]  [illegible]=1731.2  [illegible] 1391.5  [illegible]= 1351.4
          THETA = [illegible] * [illegible](EV) / Z2  /13.605(Z2) :      T(1)= 0.4534  T(2)= 0.4092  T(3)= 0.3700  T(4)= 0.4379  T(5)= 0.4253

E. J. MCGUIRE, PHYS. REV. A5, 1043 (1972):
SUBSHELL FLUORESCENCE YIELDS                          W1          W2          W3          W4          W5
                                                  [illegible]  [illegible]  [illegible]  [illegible]  [illegible]

COSTER-KRONIG PROBABILITIES        S12    S13    S14    S15    S23    S24    S25    S34    S35    F45
                                 0.256  0.827  0.031  0.099  0.126  0.667  0.120  0.143  0.751  0.40[illegible]

Z1= 13      Z2= 67                                   **** M-SHELL CROSS SECTIONS (BARN) ****

                              FIRST BORN APPROXIMATION                                              ECPSSR THEORY
                     ---------------------------------------------------------------------------------------------------------------------------
E1(MEV)  KSI RELATIV.  DIRECT + CAPTURE = IONIZATION XRAY PROD.  C/I        DIRECT + CAPTURE = IONIZATION XRAY PROD.  C/I
---------------------------------------------------------------------------------------------------------------------------------------------

 0.500     0.119     3.27E+03  4.60E+03  7.86E+03  8.67E+01  0.5867      1.33E-05  9.81E-06  2.31E-05  2.57E-07   0.4239
 0.750     0.141     1.43E+04  3.16E+04  4.59E+04  5.91E+02  0.6889      5.31E-02  2.41E-02  7.71E-02  8.62E-04   0.3119
 1.000     0.166     3.90E+04  1.18E+05  1.57E+05  1.70E+03  0.7537      2.76E+00  1.15E+00  3.91E+00  4.36E-02   0.2945
 1.250     0.185     8.05E+04  3.14E+05  3.95E+05  4.29E+03  0.7954      2.83E+01  1.27E+01  4.10E+01  4.59E-01   0.3106
 1.500     0.204     1.44E+05  6.74E+05  8.19E+05  8.86E+03  0.8240      1.34E+02  6.85E+01  2.03E+02  2.28E+00   0.3383
 1.750     0.222     2.30E+05  1.25E+06  1.48E+06  1.60E+04  0.8444      4.09E+02  2.45E+02  6.55E+02  7.33E+00   0.3749
 2.000     0.240     3.39E+05  2.07E+06  2.41E+06  2.63E+04  0.8595      9.48E+02  6.72E+02  1.62E+03  1.81E+01   0.4154
 2.250     0.255     4.67E+05  3.17E+06  3.64E+06  3.93E+04  0.8713      1.83E+03  1.53E+03  3.36E+03  3.76E+01   0.4564
 2.500     0.273     6.19E+05  4.56E+06  5.18E+06  5.59E+04  0.8806      3.11E+03  3.06E+03  6.17E+03  6.90E+01   0.4953
```

```
Z1= 13
A1= 26.98[illegible]
[illegible]          [illegible]          F[illegible]=    0.25[illegible]

Z2= 66
[illegible]= 157.50

J. A. BEARDEN [illegible] (1967): [illegible]1= 22[illegible] [illegible]2= [illegible] [illegible]3= 1211.[illegible]  [illegible]4= 1453.3  [illegible]5= 1[illegible].5
          [illegible] = [illegible] /[illegible](Z[illegible]) :       T 1= 0.[illegible]  T 2= [illegible]  T 3= [illegible].3722  T 4= [illegible]350  T 5= 0.4247

E. J. MCGUIRE, [illegible] (1972):
SUBSHELL FLUORESCENCE YIELDS          1            2            3            4            5
                                    0.001[illegible]   0.001093   0.00152[illegible]   0.037[illegible]   0.112[illegible]

COSTER-KRONIG PROBABILITIES    S12   S13   S14   S15   S23   S24   S25   S34   S35   S45
                               0.268 0.526 0.059 0.[illegible] 0.109 1.671 0.115 0.14[illegible] [illegible].754 0.[illegible]32

Z1= 13    Z2= 66                        **** M-SHELL CROSS SECTIONS (BARN) ****

                     FIRST BORN APPROXIMATION                                    ECPSSR THEORY
E1(MEV)  KSI RELATIV.  DIRECT + CAPTURE = IONIZATION XRAY PROD.  C/I      DIRECT + CAPTURE = IONIZATION XRAY PROD.  C/I

 0.500      0.115     2.57E+03  2.96E+03  5.53E+03  6.87E+01  0.5336     6.09E-06  4.95E-06  1.01E-05  1.27E-07   0.3995
 0.750      0.143     1.13E+04  2.04E+04  3.17E+04  3.91E+02  0.6433     3.16E-02  1.29E-02  4.47E-02  5.66E-04   0.2889
 1.000      0.165     3.06E+04  7.68E+04  1.02E+05  1.32E+03  0.71[illegible]     1.85E+00  6.86E-01  2.54E+00  3.19E-02   0.2706
 1.250      0.184     6.46E+04  2.06E+05  2.71E+05  3.32E+03  0.7611     2.04E+01  8.04E+00  2.84E+01  3.57E-01   0.2830
 1.500      0.202     1.16E+05  4.47E+05  5.64E+05  6.90E+03  0.7940     1.30E+02  4.49E+01  1.45E+02  1.82E+00   0.3095
 1.750      0.220     1.86E+05  8.36E+05  1.02E+06  1.25E+04  0.8177     3.15E+02  1.64E+02  4.79E+02  6.02E+00   0.3424
 2.000      0.237     2.7[illegible]E+05  1.40E+06  1.66E+06  2.05E+04  0.8357     7.63E+02  4.57E+02  1.20E+03  1.51E+01   0.3805
 2.250      0.253     3.[illegible]5E+05  2.17E+06  2.56E+06  3.12E+04  0.8496     1.46E+03  1.05E+03  2.52E+03  3.16E+01   0.4192
 2.500      0.270     5.10E+05  3.15E+06  3.66E+06  4.47E+04  0.8607     2.52E+03  2.13E+03  4.65E+03  5.64E+01   0.4578
```

```
       Z1= 13
       [illegible]
       [illegible]          [illegible]X=   [illegible]        [illegible]=   0.2[illegible]

       Z2= 7
       [illegible]= 17[illegible]

J. A. [illegible] (1967): L1= [illegible]  L2= 2173.[illegible]  L3= [illegible]  [illegible]= 1576.3  [illegible]= 1527.[illegible]
       T[illegible] = [illegible] / 72 /1[illegible] :     T 1= [illegible]  T 2= [illegible]  [illegible]  [illegible]  [illegible]= 0.4235

E. J. MCGUIRE, P[illegible] (1972):
SUBSHELL FL[illegible] YIELDS                [illegible]  [illegible]  [illegible]  [illegible]  [illegible]

COSTER-KRONIG PROBABILITIES     F12    F13    F14    F15    F23    F24    F25    F34    F35    F45
                               0.272  0.525  [illegible]  [illegible]  0.116  0.680  0.125  0.141  [illegible]  0.47[illegible]

Z1= 13     Z2= 7             **** [illegible] CROSS SECTIONS ([illegible]) ****

                  FIRST [illegible] APPROXIMATION                                        [illegible]
 E1(MEV)  KSI RELATIV.  DIRECT + CAPTURE = IONIZATION XRAY PROD.   C/I       DIRECT + CAPTURE = IONIZATION XRAY PROD.   C/I

  0.500    0.116    1.63E+03  1.30E+03  2.93E+03  4.52E+01  0.[illegible]    1.29[illegible]  7.29E-07  2.[illegible]  3.10E-08  0.3606
  0.750    0.141    7.30E+03  9.03E+03  1.63E+04  2.55E+02  0.5550    1.17E-02  3.91E-03  1.56E-02  2.41E-04  0.2506
  1.000    0.162    2.21E+04  3.44E+04  5.65E+04  8.32E+02  0.[illegible]    8.62E-01  2.5[illegible]E-01  1.12E+00  1.73E-02  0.2358
  1.250    0.181    4.27E+04  9.39E+04  1.37E+05  2.06E+03  0.6873    1.07E+01  3.36E+00  1.41E+01  2.16E-01  0.2395
  1.500    0.199    7.72E+04  2.07E+05  2.84E+05  4.33E+03  0.7283    5.73E+01  2.02E+01  7.75E+01  1.20E+00  0.2607
  1.750    0.216    1.25E+05  3.93E+05  5.18E+05  7.96E+03  0.7569    1.90E+02  7.72E+01  2.67E+02  4.14E+00  0.2887
  2.000    0.232    1.87E+05  6.72E+05  8.59E+05  1.31E+04  0.7826    4.70E+02  2.22E+02  6.92E+02  1.47E+01  0.3211
  2.250    0.243    2.62E+05  1.06E+06  1.32E+06  2.01E+04  0.8011    9.52E+02  5.27E+02  1.48E+03  2.29E+01  0.3562
  2.500    0.263    3.51E+05  1.56E+06  1.91E+06  2.91E+04  0.8162    1.69E+03  1.09E+03  2.77E+03  4.29E+01  0.3916
```

```
Z1= 13
A1= 26.98[illegible]
E[illegible]=   0.[illegible]        [illegible]X=   2.5[illegible]        [illegible]=   0.25[illegible]

Z2= 71
A2= 175.[illegible]
J. A. BEARDEN AND A. F. BURR, REV. MOD. PHYS. 39, 125 (1967): EM1= [illegible]  EM2= [illegible]  EM3= [illegible]  EM4= 1639.4  EM5= 1588.5
                 THETA = 9 * E(KEV) / Z2 /(13.605(EV)) :        TH1= [illegible]  TH2= [illegible]  TH3= 0.375[illegible]  TH4= 0.4364  TH5= 0.4729

E. J. MCGUIRE, PHYS. REV. A5, 1043 (1972):
SUBSHELL FLUORESCENCE YIELDS                          1            2            3            4            5
                                            [illegible]   [illegible]   [illegible]   [illegible]   [illegible]

COSTER-KRONIG PROBABILITIES          S12    S13    S14    S15    S23    S24    S25    S34    S35    S45
                                   0.247  0.537  0.059  [illegible]  0.115  0.573  0.125  [illegible].121  0.777  0.05[illegible]

Z1= 13     Z2= 71                                      **** M-SHELL CROSS SECTIONS (BARN) ****

                         FIRST BORN APPROXIMATION                                                     ECPSSR THEORY
E1(MEV)  KSI RELATIV.  DIRECT + CAPTURE = IONIZATION XRAY PROD.  C/I       DIRECT + CAPTURE = IONIZATION XRAY PROD.  C/I

 0.500     0.116      1.29E+03  8.78E+02  2.17E+03  3.75E+01  0.40[illegible]     5.70E-07  2.95E-07  8.65E-07  1.48E-08  0.3411
 0.750     0.140      5.37E+03  6.09E+03  1.1[illegible]E+04  4.05E+02  0.5[illegible]     6.8[illegible]E-03  2.13E-03  8.97E-03  1.55E-04  0.2340
 1.000     0.161      1.63E+04  2.33E+04  3.96E+04  [illegible]E+02  0.5893     5.77E-01  1.56E-01  7.33E-01  1.27E-02  0.2127
 1.250     0.180      3.48E+04  5.41E+04  8.89E+04  1.7[illegible]E+03  0.6[illegible]     7.70E+00  2.17E+00  9.86E+00  1.71E-01  0.2195
 1.500     0.197      6.31E+04  1.42E+05  2.06E+05  3.53E+03  0.6[illegible]     4.29E+01  1.34E+01  5.63E+01  9.74E-01  0.2383
 1.750     0.214      1.03E+05  2.73E+05  3.76E+05  6.45E+03  0.7266     1.47E+02  5.25E+01  1.99E+02  3.45E+00  0.2637
 2.000     0.230      1.54E+05  4.70E+05  6.24E+05  1.07E+04  0.7530     3.70E+02  1.54E+02  5.24E+02  9.07E+00  0.2938
 2.250     0.245      2.16E+05  7.45E+05  9.63E+05  1.65E+04  0.77[illegible]     7.63E+02  3.7[illegible]E+02  1.13E+03  1.96E+01  0.3263
 2.500     0.260      2.93E+05  1.11E+06  1.40E+06  2.40E+04  0.7910     1.37E+03  7.70E+02  2.14E+03  3.70E+01  0.3603
```

```
              Z1= 13
              A1= 26.9[illegible]
              EB1=   [illegible]        [illegible]=   [illegible]        [illegible]    0.25[illegible]

              Z2= 72
              A2= 17[illegible]

J. A. [illegible] (1967): [illegible]1= [illegible]  [illegible]2= 23[illegible]  [illegible]3= 2107.[illegible]  [illegible]4= 1716.8  [illegible]5= 1661.7
              THETA = 2 * [illegible](EC) / Z2 / 10.[illegible](EC) :       T1= 0.9062  T2= 0.[illegible]  T3= 0.3779  T4= 0.[illegible]391  T5= 0.4251

E. J. MCGUIRE, PHYS. REV. A5, 1043 (1972):
SUBSHELL FLUORESCENCE YIELDS                               0.0[illegible]   0.00[illegible]   0.0[illegible]   0.[illegible]   0.[illegible]

COSTER-KRONIG PROBABILITIES          S12    S13    S14    S15    S23    S24    S25    S34    S35    S45
                                   0.222  0.549  0.021  0.107  0.115  0.074  0.134  0.122  0.794  0.43[illegible]

Z1= 13    Z2= 72                            **** [illegible] CROSS SECTIONS (BARN) ****

                              FIRST BORN APPROXIMATION                                            ECPSSR THEORY
               ********************************************************************************************************
E1(MEV)  KSI RELATIV.  DIRECT + CAPTURE = IONIZATION XRAY PROD.  C/I        DIRECT + CAPTURE = IONIZATION XRAY PROD.  C/I
------------------------------------------------------------------------------------------------------------------------

 0.500      0.115      9.87E+02  5.54E+02  1.54E+03  2.93E+01  0.3594       2.34E-07  1.11E-07  3.45E-07  6.50E-09  0.3215
 0.750      0.139      4.52E+03  3.84E+03  8.35E+03  1.59E+02  0.4593       3.85E-03  1.07E-03  4.91E-03  9.31E-05  0.2168
 1.000      0.159      1.26E+04  1.48E+04  2.74E+04  5.19E+02  0.5394       3.66E-01  8.95E-02  4.5[illegible]E-01  8.7[illegible]E-03  0.1956
 1.250      0.178      2.70E+04  4.09E+04  6.78E+04  1.29E+03  0.6015       5.29E+00  1.33E+00  6.61E+00  1.26E-01  0.2006
 1.500      0.195      4.94E+04  9.13E+04  1.41E+05  2.67E+03  0.6497       3.10E+01  8.54E+00  3.95E+01  7.53E-01  0.2161
 1.750      0.211      8.08E+04  1.76E+05  2.57E+05  4.87E+03  0.6859       1.10E+02  3.43E+01  1.44E+02  2.75E+00  0.2377
 2.000      0.227      1.22E+05  3.06E+05  4.28E+05  8.11E+03  0.7153       2.84E+02  1.02E+02  3.86E+02  7.37E+00  0.2650
 2.250      0.242      1.73E+05  4.90E+05  6.63E+05  1.26E+04  0.7389       5.96E+02  2.50E+02  8.46E+02  1.61E+01  0.2953
 2.500      0.257      2.34E+05  7.35E+05  9.69E+05  1.84E+04  0.7585       1.09E+03  5.26E+02  1.61E+03  3.07E+01  0.3266
```

```
        Z1= 13
        A1= 26.98
        E(1)= [illegible]        [illegible]X=  [illegible]        [illegible]=   0.2300

        Z2= 79
        A2= 197.0

J. A. BEARDEN [illegible] PHYS. 39, 125 (1967): [illegible]  [illegible]= 31[illegible]  [illegible]= 27[illegible]  [illegible]= 2291.1  [illegible]= 2291.7
                  THETA = 9 * [illegible](EV) / Z2** /13.605(EV) :    TH1= [illegible]  TH2= [illegible]  TH3= 0.3[illegible]  TH4= [illegible]  TH5= 0.4360

E. J. MCGUIRE, PHYS. REV. A5, 1043 (1972):
SUBSHELL FLUORESCENCE YIELDS            0.00213   0.00423   0.00480   0.00[illegible]   [illegible]

COSTER-KRONIG PROBABILITIES       S12    S13    S14    S15    S23    S24    S25    S34    S35    F45
                                 0.188  0.59   0.367  0.112  0.119  [illegible]  0.825  [illegible]  0.722  [illegible]

Z1= 13    Z2= 79                              **** M-SHELL CROSS SECTIONS (BARN) ****

                                       FIRST BORN APPROXIMATION                                  ECPSSR THEORY
 E1(MEV)  KSI RELATIV.  DIRECT + CAPTURE = IONIZATION XRAY PROD.  C/T       DIRECT + CAPTURE = IONIZATION XRAY PROD.  C/I

  0.500     0.1[illegible]     1.74E+02  3.38E+01  2.08E+02  5.67E+00  0.1623     2.97E-10  6.35E-11  3.61E-10  1.04E-11   0.2193
  0.750     0.131     8.47E+02  2.31E+02  1.08E+03  2.92E+01  0.2142     5.53E-05  8.49E-06  6.38E-05  1.75E-06   0.1331
  1.000     0.15[illegible]     2.47E+03  8.97E+02  3.37E+03  9.05E+01  0.2665     1.40E-02  1.91E-03  1.59E-02  4.61E-04   0.1133
  1.250     0.167     5.50E+03  2.54E+03  8.04E+03  2.16E+02  0.3161     3.82E-01  4.71E-02  4.29E-01  1.18E-02   0.1098
  1.500     0.182     1.04E+04  5.87E+03  1.62E+04  4.34E+02  0.3619     3.16E+00  4.11E-01  3.57E+00  9.81E-02   0.1151
  1.750     0.197     1.74E+04  1.18E+04  2.92E+04  7.80E+02  0.4029     1.43E+01  2.02E+00  1.63E+01  4.46E-01   0.1237
  2.000     0.210     2.72E+04  2.13E+04  4.83E+04  1.29E+03  [illegible]     4.41E+01  6.9[illegible]E+00  5.10E+01  1.53E+00   0.1360
  2.250     0.223     3.95E+04  3.54E+04  7.49E+04  1.99E+03  0.4739     1.06E+02  1.[illegible]E+01  1.23E+02  3.44E+00   0.1503
  2.500     0.236     5.49E+04  5.54E+04  1.10E+05  2.93E+03  0.5021     2.16E+02  4.31E+01  2.59E+02  7.12E+00   0.1665
```

```
Z1= 13
A1= 26.98
E.I.= [illegible]          X= [illegible]          RATIO= [illegible]

Z2= 82
A2= 207.20

J. A. BEARDEN [illegible] REV. MOD. PHYS. 39, 125 (1967): EM1= [illegible] EM2= [illegible] EM3= [illegible] EM4= 2585.6 EM5= 2484.0
         THETA = 4 * E(EV) / Z2 /13.605(EV) :         TH1= 1.508  TH2= 0.4637  TH3= 0.4862  TH4= 0.4019  TH5= 0.4038

E. J. MCGUIRE, PHYS. REV. A5, 1043 (1972):
SUBSHELL FLUORESCENCE YIELDS                    W1          W2          W3          W4          W5
                                             0.00270     0.01535     0.0155      [illegible] 0.01373

COSTER-KRONIG PROBABILITIES          S12    S13    S14    S15    S23    S24    S25    S34    S35    F45
                                    0.113  0.633  0.066  0.099  0.106  0.261  0.446  0.102  0.713  0.036

Z1= 13     Z2= 82                            **** M-SHELL CROSS SECTIONS (BARN) ****

                         FIRST BORN APPROXIMATION                                          ECPSSR  THEORY
                  ---------------------------------------------------------------------------------------------------------------
EI(MEV)  KSI RELATIV.  DIRECT + CAPTURE = IONIZATION XRAY PROD.  C/T          DIRECT + CAPTURE = IONIZATION XRAY PROD.  C/T
-------------------------------------------------------------------------------------------------------------------------------

 0.500     0.106     8.05E+01  1.07E+01  9.13E+01  2.91E+00   0.1171       1.19E-11  2.69E-12  1.46E-11  4.61E-13   0.1843
 0.750     0.123     4.05E+02  7.24E+01  4.77E+02  1.52E+01   0.1517       7.24E-06  8.89E-07  8.13E-06  2.58E-07   0.1093
 1.000     0.136     1.21E+03  2.81E+02  1.49E+03  4.72E+01   0.1890       3.29E-03  3.27E-04  3.61E-03  1.15E-04   0.0904
 1.250     0.162     2.73E+03  8.09E+02  3.53E+03  1.12E+02   0.2268       1.10E-01  1.05E-02  1.20E-01  3.63E-03   0.0869
 1.500     0.177     5.20E+03  1.86E+03  7.07E+03  2.23E+02   0.2636       1.09E+00  1.07E-01  1.20E+00  3.81E-02   0.0890
 1.750     0.191     8.87E+03  3.77E+03  1.26E+04  3.99E+02   0.2963       5.53E+00  5.78E-01  6.11E+00  1.95E-01   0.0946
 2.000     0.204     1.39E+04  6.88E+03  2.08E+04  6.56E+02   0.3306       1.87E+01  2.15E+00  2.08E+01  6.63E-01   0.1026
 2.250     0.216     2.05E+04  1.16E+04  3.21E+04  1.01E+03   0.3613       4.92E+01  5.09E+00  5.43E+01  1.73E+00   0.1121
 2.500     0.228     2.88E+04  1.84E+04  4.72E+04  1.49E+03   0.3901       1.03E+02  1.45E+01  1.17E+02  3.74E+00   0.1239
```

```
                    Z1= 13
                    A1= 26.9[illegible]
                    F(?)=   0.[illegible]        [illegible]=   [illegible]        [illegible]=   0.25[illegible]

                    Z2= 53
                    A2= [illegible]

 J. A. BEARDEN AND A. F. BURR, REV. MOD. PHYS. 39, 125 (1967): L1= 5[illegible].1  L2= 53[illegible].4  L3= 517[illegible]  L4= 2637.6  L5= 2573.6
                    THETA = 9 * I (EV) / Z2**2/13.6[illegible](Z2) :       T1= 0.[illegible]  T2= 0.[illegible]  T3= 0.8[illegible]2  T4= 0.6640  T5= 0.8461

 E. J. MCGUIRE, PHYS. REV. A9, 1[illegible]43 (197[illegible]):
 SUBSHELL FLUORESCENCE YIELDS                       W1           W2          W3          W4          W5
                                               0.0[illegible]    0.0652      0.1253      0.[illegible]    0.032[illegible]

 COSTER-KRONIG PROBABILITIES          S12    S13    S14    S15    S23    S24    S25    S34    S35    S45
                                     0.169  0.651  0.045  0.295  0.103  0.464  0.033  0.[illegible]  0.756  0.[illegible]

 Z1= 13    Z2= 53                                    **** L-SHELL CROSS SECTIONS (BARN) ****

                                      FIRST BORN APPROXIMATION                                  ECPSSR THEORY
 E1(MEV)  KSI RELATIV.  DIRECT + CAPTURE = IONIZATION XRAY PROD.  C/I          DIRECT + CAPTURE = IONIZATION XRAY PROD.  C/I

  0.500      0.105      6.29E+01  7.45E+00  7.04E+01  2.34E+00  0.1059      3.07E-12  8.23E-13  6.65E-12  1.55E-13  0.1755
  0.750      0.127      3.19E+02  5.03E+01  3.69E+02  1.23E+01  0.1364      3.59E-05  4.13E-07  6.01E-06  1.32E-07  0.1031
  1.000      0.145      9.59E+02  1.95E+02  1.15E+03  3.85E+01  0.1603      1.95E-03  1.61E-04  2.13E-03  7.07E-05  0.0847
  1.250      0.161      2.18E+03  5.57E+02  2.74E+03  9.00E+01  0.2132      7.25E-02  6.35E-03  7.86E-02  2.61E-03  0.0807
  1.500      0.175      4.18E+03  1.30E+03  5.48E+03  1.82E+02  0.2379      7.66E-01  6.83E-02  8.34E-01  2.77E-02  0.0819
  1.750      0.189      7.14E+03  2.63E+03  9.77E+03  3.24E+02  0.2696      4.05E+00  3.84E-01  4.42E+00  1.47E-01  0.0870
  2.000      0.202      1.12E+04  4.82E+03  1.61E+04  5.32E+02  0.3001      1.40E+01  1.45E+00  1.55E+01  5.13E-01  0.0990
  2.250      0.214      1.66E+04  8.15E+03  2.48E+04  8.20E+02  0.3290      3.69E+01  4.23E+00  4.11E+01  1.37E+00  0.1028
  2.500      0.225      2.34E+04  1.29E+04  3.63E+04  1.20E+03  0.3550      8.03E+01  1.02E+01  9.05E+01  3.01E+00  0.1130
```

```
                   Z1= 13
                   A1= 26.98
                   E.I.= [illegible]          X= [illegible]          F.U.L.=   0.25[illegible]

                   Z2= 92
                   A2= 238.0[illegible]

 J. A. BEARDEN AND A. F. BURR, REV. MOD. PHYS. 39, 125 (1967): [illegible]   = 3727.6   M1= 5551.7
                   THETA = 4 * [illegible] / Z2 /13.6(EV) :      TH1= [illegible]  TH2= 0.5237  TH3= 0.5506  TH4= 0.7012  TH5= 0.4681

 E. J. MCGUIRE, PHYS. REV. A5, 1043 (1972):
 SUBSHELL FLUORESCENCE YIELDS                    [illegible]   [illegible]   [illegible]   [illegible]   [illegible]

 COSTER-KRONIG PROBABILITIES        F12    F13    F14    F15    F23    F24    F25    F34    F35    F45
                                   0.036  [illegible]  [illegible]  0.027  0.110  [illegible]  [illegible]  [illegible]  [illegible]  [illegible]

 Z1= 13    Z2= 92                          **** M-SHELL IONIZATION CROSS SECTIONS (BARN) ****

                       FIRST BORN APPROXIMATION                                         ECPSSR THEORY
 E1(MEV)  KSI RELATIV.  DIRECT + CAPTURE = IONIZATION XRAY PROD.  C/T      DIRECT + CAPTURE = IONIZATION XRAY PROD.  C/T

  0.500     0.099     7.35E+00  3.58E-01  7.71E+00  4.51E-01  0.0465     6.44E-17  8.29E-18  7.27E-17  4.19E-18  0.1141
  0.750     0.111     3.95E+01  2.35E+00  4.22E+01  2.46E+00  0.0584     4.10E-09  2.73E-10  4.37E-09  2.56E-10  0.0624
  1.000     0.133     1.27E+02  9.22E+00  1.37E+02  8.06E+00  0.0675     1.38E-05  7.04E-07  1.45E-05  8.30E-07  0.0487
  1.250     0.148     3.04E+02  2.54E+01  3.31E+02  1.96E+01  0.0768     1.36E-03  6.29E-05  1.43E-03  8.22E-05  0.0441
  1.500     0.162     6.09E+02  6.22E+01  6.71E+02  3.99E+01  0.0927     2.61E-02  1.19E-03  2.73E-02  1.58E-03  0.0434
  1.750     0.174     1.06E+03  1.26E+02  1.19E+03  7.18E+01  0.1063     2.03E-01  9.61E-03  2.13E-01  1.26E-02  0.0442
  2.000     0.186     1.70E+03  2.38E+02  1.94E+03  1.19E+02  0.1228     9.78E-01  4.65E-02  1.02E+00  5.92E-02  0.0461
  2.250     0.196     2.64E+03  4.10E+02  3.05E+03  1.83E+02  0.1343     3.18E+00  1.64E-01  3.34E+00  1.95E-01  0.0490
  2.500     0.206     3.81E+03  6.64E+02  4.47E+03  2.69E+02  0.1485     8.23E+00  4.56E-01  8.69E+00  5.05E-01  0.0525
```

APPENDIX F

Theoretical M-shell ionization and x-ray production cross sections for incident $^{40}_{18}Ar^+$ ions upon Pr, Nd, Eu, Gd, Dy, Ho, Er, YB, Lu, Hf, Au, Pb, Bi, and U.

```
Z1= 13
A1= [illegible]
[illegible]              [illegible]                  0.25[illegible]

Z2= [illegible]
A2= [illegible]

J. A. BEARDEN [illegible] (1967): [illegible]
                    THETA = [illegible] / Z2 [illegible]       [illegible] TH4= 0.4593 TH5= 0.4299

E. J. MCGUIRE, PHYS. REV. A5, 1043 (1972):
SUBSHELL FLUORESCENCE YIELDS             1           2           3           4           5
                                   [illegible]  0.0[illegible]  [illegible]  [illegible]  [illegible]

COSTER-KRONIG PROBABILITIES     F12   F13   F14   F15   F23   F24   F25   F34   F35   F45
                              0.222 0.495 0.092 0.132 0.049 0.613 0.259 0.182 0.721 0.233

Z1= 13    Z2= [illegible]                              **** [illegible] CROSS SECTIONS [illegible] ****

                                  FIRST BORN APPROXIMATION                                  ECPSSR THEORY
                  ---------------------------------------------------------------------------------------------------------
EI(MEV)  KSI RELATIV.  DIRECT + CAPTURE = IONIZATION XRAY PROD.  C/I     DIRECT + CAPTURE = IONIZATION XRAY PROD.  C/I
---------------------------------------------------------------------------------------------------------------------------

  0.500     0.065     1.15E+04  1.86E+07  1.86E+07  4.74E+04  0.9994     2.35E-09  1.91E-06  1.96E-06  4.57E-09  0.9989
  0.750     0.103     5.13E+04  9.44E+07  9.44E+07  2.41E+05  0.9995     3.17E-04  3.29E-02  3.29E-02  8.01E-05  0.9904
  1.000     0.118     1.41E+05  2.54E+08  2.54E+08  6.52E+05  0.9994     8.11E-02  3.53E+00  3.67E+00  9.04E-03  0.9779
  1.250     0.133     2.99E+05  4.93E+08  4.93E+08  1.27E+06  0.9994     2.07E+00  6.35E+01  6.56E+01  1.63E-01  0.9665
  1.500     0.145     5.37E+05  7.87E+08  7.87E+08  2.03E+06  0.9993     1.78E+01  4.66E+02  4.85E+02  1.21E+00  0.9634
  1.750     0.159     8.63E+05  1.11E+09  1.11E+09  2.86E+06  0.9992     8.31E+01  2.09E+03  2.17E+03  5.43E+00  0.9617
  2.000     0.172     1.25E+06  1.43E+09  1.43E+09  3.70E+06  0.9991     2.67E+02  6.79E+03  7.05E+03  1.77E+01  0.9622
  2.250     0.184     1.76E+06  1.73E+09  1.73E+09  4.49E+06  0.9990     6.67E+02  1.78E+04  1.84E+04  4.64E+01  0.9638
  2.500     0.196     2.36E+06  2.01E+09  2.01E+09  5.22E+06  0.9988     1.40E+03  3.97E+04  4.11E+04  1.04E+02  0.9660
```

```
          Z1= 18
          M1= 3[illegible].[illegible]5[illegible]
          EMIN= 0.50000        EMAX= 2.50000        ESTEP= 0.25000

          Z2= 60
          M2= 144.2[illegible]
J. A. BEARDEN, A. F. BURR, REV. MOD. PHYS. 39, 125 (1967): UM1= 1575.3  UM2= 14[illegible]  UM3= 1297.[illegible]  UM4= [illegible]99.9  UM5= 977.7
          THETA = 9 * U(EV) / Z2**2/13.605(EV) :       TM1= 0.4380  TM2= 0.3905  TM3= 0.3[illegible]11  TM4= 0.4562  TM5= 0.4285

E. J. MCGUIRE, PHYS. REV. A5, 1043 (1972):
SUBSHELL FLUORESCENCE YIELDS                      W1           W2           W3           W4           W5
                                             [illegible]   0.001325     0.001751     0.002[illegible]  0.00[illegible]

COSTER-KRONIG PROBABILITIES          S12    S13    S14    S15    S23    S24    S25    S34    S35    F45
                                    0.236  0.489  0.092  0.120  0.057  0.645  0.172  0.174  0.712  0.267

 Z1= 18     Z2= 60                          **** M-SHELL CROSS SECTIONS (BARN) ****

                              FIRST BORN APPROXIMATION                                          ECPSSR THEORY
                  ---------------------------------------------------------------------------------------------------------
 E1(MEV)  KSI RELATIV.  DIRECT + CAPTURE = IONIZATION XRAY PROD.  C/I         DIRECT + CAPTURE = IONIZATION XRAY PROD.  C/I
 ---------------------------------------------------------------------------------------------------------------------------

  0.500      0.086      8.64E+03  7.46E+06  7.47E+06  2.47E+04   0.9988       6.64E-10  4.64E-07  4.64E-07  1.84E-09   0.9986
  0.750      0.102      3.96E+04  4.12E+07  4.12E+07  1.36E+05   0.9990       1.57E-04  1.21E-02  1.22E-02  4.86E-05   0.9872
  1.000      0.118      1.09E+05  1.13E+08  1.13E+08  3.95E+05   0.9991       4.73E-02  1.58E+00  1.63E+00  6.48E-03   0.9706
  1.250      0.132      2.32E+05  2.47E+08  2.47E+08  8.15E+05   0.9991       1.34E+00  3.06E+01  3.20E+01  1.27E-01   0.9581
  1.500      0.145      4.20E+05  4.16E+08  4.16E+08  1.37E+06   0.9990       1.23E+01  2.38E+02  2.50E+02  9.96E-01   0.9510
  1.750      0.158      6.79E+05  6.14E+08  6.14E+08  2.03E+06   0.9989       5.94E+01  1.10E+03  1.16E+03  4.62E+00   0.9488
  2.000      0.170      1.01E+06  8.26E+08  8.27E+08  2.73E+06   0.9988       1.96E+02  3.67E+03  3.86E+03  1.54E+01   0.9494
  2.250      0.182      1.42E+06  1.04E+09  1.04E+09  3.43E+06   0.9986       5.00E+02  9.79E+03  1.03E+04  4.09E+01   0.9514
  2.500      0.194      1.69E+06  1.25E+09  1.25E+09  4.12E+06   0.9985       1.07E+03  2.22E+04  2.33E+04  9.24E+01   0.9543
```

```
        Z1= 1.
        A1= 37.95)
        ETIL=    [illegible]        [illegible]=    2.50+[illegible]        FSTEP=    0.250[illegible]

        Z2= 63
        A2= 152.[illegible]

J. A. BEARDEN AND A. F. BURR, REV. MOD. PHYS. 39, 125 (1967): EM1= 1[illegible]   EM2= 15[illegible]   EM3= 1[illegible]   EM4= 1160.5   EM5= 1135.9
        THETA = 9 * B(EV) / Z2  /13.605(EV) :        TM1= 0.4606   TM2= 0.5057   TM3= 0.5557   TM4= 0.4384   TM5= 0.4271

E. J. MCGUIRE, PHYS. REV. A5, 1043 (1972):
SUBSHELL FLUORESCENCE YIELDS                    1            2            3            4            5
                                         0.00117[illegible]   0.00147[illegible]   0.00136[illegible]   0.00312[illegible]   0.00[illegible]

COSTER-KRONIG PROBABILITIES         S12   S13   S14   S15   S23   S24   S25   S34   S35   S45
                                  0.333 0.445 0.071 0.100 0.062 0.519 0.127 0.163 0.7[illegible]0 0.364

 Z1= 18    Z2= 63                        **** M-SHELL CROSS SECTIONS (BARN) ****

                          FIRST BORN APPROXIMATION                                          ECPSSR THEORY
                 -----------------------------------------------------------------------------------------------
 E1(MEV)  KSI RELATIV.  DIRECT + CAPTURE = IONIZATION XRAY PROD.  C/I        DIRECT + CAPTURE = IONIZATION XRAY PROD.  C/I
 -------------------------------------------------------------------------------------------------------------------

  0.500     0.083     3.85E+03  5.75E+05  5.79E+05  3.52E+03   0.9933      1.63E-11  5.26E-09  5.27E-09  3.44E-11   0.9969
  0.750     0.101     1.77E+04  3.60E+06  3.62E+06  2.31E+04   0.9954      1.58E-05  5.67E-04  5.83E-04  3.79E-06   0.9729
  1.000     0.116     4.97E+04  1.30E+07  1.30E+07  7.87E+04   0.9962      9.70E-03  1.32E-01  1.42E-01  9.13E-04   0.9360
  1.250     0.129     1.07E+05  3.10E+07  3.11E+07  1.86E+05   0.9966      3.34E-01  3.43E+00  3.76E+00  2.44E-02   0.9112
  1.500     0.142     1.97E+05  5.97E+07  5.99E+07  3.62E+05   0.9967      3.66E+00  3.18E+01  3.54E+01  2.30E-01   0.8967
  1.750     0.153     3.24E+05  9.92E+07  9.96E+07  6.01E+05   0.9967      2.04E+01  1.65E+02  1.85E+02  1.20E+00   0.8902
  2.000     0.165     4.90E+05  1.49E+08  1.49E+08  9.09E+05   0.9967      7.36E+01  5.99E+02  6.72E+02  4.36E+00   0.8906
  2.250     0.176     6.96E+05  2.06E+08  2.07E+08  1.23E+06   0.9966      2.22E+02  1.70E+03  1.91E+03  1.23E+01   0.8943
  2.500     0.187     9.46E+05  2.70E+08  2.71E+08  1.64E+06   0.9965      4.55E+02  4.08E+03  4.53E+03  2.93E+01   0.8996
```

```
          Z1= 1[illegible]
          A1= 39.950
          E1T.=    [illegible]         [illegible]=    [illegible]        [illegible]=    0.25000

          Z2= [illegible]
          A2= 1[illegible]7.3[illegible]

J. A. BEARDEN AND A. F. BURR, REV. MOD. PHYS. 39, 125 (1967): [illegible]= 1[illegible]  [illegible]= 16[illegible]  [illegible]= 1[illegible]  [illegible]= 12[illegible]7.2  [illegible]= 1165.2
          THETA = 9 * [illegible] / Z2[illegible] /13.6[illegible]([illegible]) :        T[illegible]1= [illegible]  T[illegible]= [illegible]  T[illegible]= [illegible].3[illegible]71  T[illegible]= [illegible].4365  T[illegible]= 0.4276

E. J. [illegible], PHYS. REV. [illegible], 10[illegible] (1972):
SUBSHELL FLUORESCENCE YIELDS
                                        0.[illegible]  0.[illegible]  0.[illegible]  [illegible]  0.[illegible]

COSTER-KRONIG PROBABILITIES         S12   S13   S14   S15   S23   S24   S25   S34   S35   F45
                                   0.320 [illegible] [illegible] [illegible] 0.073 [illegible] 0.1[illegible] [illegible] 0.7[illegible] [illegible]

.Z1= 18    Z2= 64                             **** [illegible]-SHELL CROSS SECTIONS ([illegible]) ****

                                   FIRST BORN APPROXIMATION                                     ECPSS  THEORY
E1(MEV)  KSI RELATIV.  DIRECT + CAPTURE = IONIZATION XRAY PROD.  C/I       DIRECT + CAPTURE = IONIZATION XRAY PROD.  C/I

 0.500      0.085      2.96E+03  2.67E+05  2.70E+05  1.97E+03  0.9930     5.02E-12  1.27E-09  1.27E-09  9.76E-12  0.9961
 0.750      0.100      1.37E+04  1.83E+06  1.84E+06  1.34E+04  0.9926     7.53E-06  2.17E-04  2.24E-04  1.72E-06  0.9662
 1.000      0.115      3.35E+04  6.49E+06  6.52E+06  4.72E+04  0.9941     5.05E-03  6.06E-02  6.56E-02  5.63E-04  0.9233
 1.250      0.128      8.37E+04  1.61E+07  1.62E+07  1.17E+05  0.9948     2.13E-01  1.74E+00  1.95E+00  1.49E-02  0.8909
 1.500      0.140      1.54E+05  3.20E+07  3.21E+07  2.32E+05  0.9952     2.49E+00  1.71E+01  1.96E+01  1.49E-01  0.8728
 1.750      0.152      2.54E+05  5.48E+07  5.51E+07  3.95E+05  0.9954     1.46E+01  9.21E+01  1.07E+02  8.14E-01  0.8647
 2.000      0.163      3.87E+05  8.45E+07  8.49E+07  6.14E+05  0.9954     5.36E+01  3.43E+02  3.97E+02  3.03E+00  0.8645
 2.250      0.174      5.54E+05  1.20E+08  1.21E+08  6.74E+05  0.9954     1.51E+02  9.97E+02  1.15E+03  8.76E+00  0.8685
 2.500      0.165      7.54E+05  1.61E+08  1.62E+08  1.17E+06  0.9954     3.47E+02  2.42E+03  2.77E+03  2.11E+01  0.8749
```

```
[illegible]
                                   [illegible]          [illegible]        E_TLP=     0.2[illegible]

[illegible]

J. [illegible] (1967): [illegible]  [illegible]= 2231.[illegible]  [illegible]= 1577.[illegible]  [illegible]= 1332.5  [illegible]= 1291.7
           [illegible] = [illegible] * [illegible] / [illegible] /13.605(Z[illegible]) :      [illegible]= 0.4517  [illegible]= 0.1665  [illegible]= 0.3993  [illegible]= 0.4382  [illegible]= 0.4256

F. J. MCGUIRE, PHYS. REV. A5, 1043 (1972):
SUBSHELL FLUORESCENCE YIELDS                    1           2           3           4           5
                                           0.01103     0.001762    [illegible]  [illegible]  [illegible]

COSTER-KRONIG PROBABILITIES    F12    F13    F14    F15    F23    F24    F25    F34    F35    F45
                              0.288  0.516  0.063  0.093  0.095  0.629  0.124  0.15[illegible]  0.7[illegible]3  0.39[illegible]

ZI= 16    Z2= 66                            **** M-SHELL CROSS SECTIONS (BARN) ****

                        FIRST BORN APPROXIMATION                                               ECPSSR THEORY
               -----------------------------------------------------------------------------------------------------------
EI(MEV)  KSI RELATIV.  DIRECT + CAPTURE = IONIZATION XRAY PROD.   C/I       DIRECT + CAPTURE = IONIZATION XRAY PROD.   C/I
---------------------------------------------------------------------------------------------------------------------------

 0.500      0.072      1.77E+03  6.75E+04  6.92E+04  6.07E+02   0.9745     3.67E-15  6.29E-11  6.29E-11  6.21E-13   0.9942
 0.750      0.099      8.33E+03  4.85E+05  4.93E+05  4.73E+03   0.9831     1.53E-06  2.98E-05  3.13E-05  3.09E-07   0.9512
 1.000      0.114      2.37E+04  1.62E+06  1.64E+06  1.72E+04   0.9871     1.54E-03  1.27E-02  1.42E-02  1.41E-04   0.8952
 1.250      0.127      5.29E+04  4.76E+06  4.81E+06  4.60E+04   0.9892     8.39E-02  4.49E-01  5.32E-01  5.26E-03   0.8441
 1.500      0.139      9.70E+04  9.97E+06  1.01E+07  9.62E+04   0.9904     1.11E+00  5.00E+00  6.11E+00  6.07E-02   0.8180
 1.750      0.150      1.61E+05  1.80E+07  1.81E+07  1.73E+05   0.9911     7.66E+00  2.93E+01  3.69E+01  3.61E-01   0.8058
 2.000      0.161      2.47E+05  2.90E+07  2.92E+07  2.79E+05   0.9916     2.61E+01  1.16E+02  1.42E+02  1.43E+00   0.8045
 2.250      0.171      3.56E+05  4.31E+07  4.35E+07  4.15E+05   0.9918     8.36E+01  3.51E+02  4.34E+02  4.31E+00   0.8090
 2.500      0.182      4.89E+05  6.02E+07  6.07E+07  5.75E+05   0.9919     1.93E+02  8.65E+02  1.05E+03  1.07E+01   0.8170
```

```
           Z1= 18
           M1= 39.950
           FH2=    0.0[illegible]     EMAX=    [illegible]     FUTURE    0.2[illegible]

           Z2= 67
           M2= 164.9[illegible]

J. A. BEARDEN AND A. F. BURR, REV. MOD. PHYS. 39, 125 (1967): U1= 2[illegible]  U2= 1922.[illegible]  U3= 1741.2  U4= 1391.5  U5= 1351.4

           THETA = U * U(EV) / Z2* /13.6(EV) :        T1= 0.4530  T2= 0.[illegible]92  T3= 0.3736  T4= 0.[illegible]379  T5= 0.4253

E. J. MCGUIRE, PHYS. REV. A5, 1043 (1972):
SUBSHELL FLUORESCENCE YIELDS                       1            2             3             4            5
                                            [illegible]   0.001253      0.0[illegible]57  0.0067[illegible]  [illegible]

COSTER-KRONIG PROBABILITIES          S12    S13    S14    S15    S23    S24    S25    S34    S35    F45
                                    0.265  0.527  0.061  0.090  0.106  1.067  0.120  0.140  0.711  [illegible]

Z1= 18     Z2= 67                           **** SUBSHELL CROSS SECTIONS (BARN) ****

                    FIRST BORN APPROXIMATION                                           ECPSS  THEORY
 E1(MEV)  KSI RELATIV.  DIRECT + CAPTURE = IONIZATION XRAY PROD.  C/I         DIRECT + CAPTURE = IONIZATION XRAY PROD.  C/I

  0.500      0.082       1.37E+05  3.61E+04  3.75E+04  4.07E+02  0.9650      9.75E-14  1.41E-11  1.42E-11  1.57E-13  0.9931
  0.750      0.099       6.55E+03  2.63E+05  2.72E+05  2.92E+03  0.9757      6.89E-07  1.13E-05  1.20E-05  1.33E-07  0.9425
  1.000      0.113       1.20E+04  1.00E+06  1.02E+06  1.17E+04  0.9816      8.72E-04  5.94E-03  6.62E-03  7.57E-05  0.6720
  1.250      0.126       4.14E+04  2.69E+06  2.73E+06  2.94E+04  0.9848      5.19E-02  2.35E-01  2.87E-01  3.20E-03  0.6193
  1.500      0.138       7.72E+04  5.74E+06  5.82E+06  6.27E+04  0.9867      7.47E-01  2.79E+00  3.54E+00  3.95E-02  0.7891
  1.750      0.149       1.23E+05  1.05E+07  1.07E+07  1.15E+05  0.9879      4.98E+00  1.71E+01  2.21E+01  2.46E-01  0.7743
  2.000      0.159       1.97E+05  1.73E+07  1.75E+07  1.89E+05  0.9887      2.05E+01  6.95E+01  9.00E+01  1.00E+00  0.7724
  2.250      0.170       2.87E+05  2.63E+07  2.66E+07  2.86E+05  0.9892      6.16E+01  2.16E+02  2.77E+02  3.09E+00  0.7774
  2.500      0.180       3.95E+05  3.73E+07  3.77E+07  4.06E+05  0.9895      1.56E+02  5.52E+02  7.08E+02  7.84E+00  0.7859
```

```
           Z1= 1.
           M1= [illegible]
           E1/M1= [illegible]      [illegible]= [illegible]      [illegible]= [illegible]

           Z2= [illegible]
           M2= 1[illegible]

J. [illegible] (19[illegible]): [illegible]= [illegible]   [illegible]= 1[illegible]   [illegible]= 1553.3   [illegible]= 1[illegible].5
           [illegible] = 8 * [illegible] / 33 [illegible] :      T[illegible]= [illegible]   [illegible]= [illegible]   [illegible]= [illegible]   [illegible]= [illegible]   T[illegible]= 0.4247

E. J. MCGUIRE, PHYS. REV. A5, 1[illegible]43 (1972):
SUBSHELL FLUORESCENCE YIELDS
                                      [illegible]2.32   [illegible]   [illegible]   [illegible]   0.012[illegible]

COSTER-KRONIG PROBABILITIES    f12    f13    f14    f15    S23    S24    S25    S34    S35    F45
                             0.258  0.50[illegible]  0.0[illegible]  [illegible]  0.109  [illegible].271  0.115  [illegible].14[illegible]  [illegible]  [illegible].032

Z1= 18    Z2= [illegible]              **** [illegible] CROSS SECTIONS ([illegible]) ****

                    FIRST BORN APPROXIMATION                                          ECPSSR THEORY
E1(MEV)  KSI RELATIV.  DIRECT + CAPTURE = IONIZATION XRAY PROD.  C/I        DIRECT + CAPTURE = IONIZATION XRAY PROD.  C/I

0.500     0.081      1.99E+03  1.97E+04  2.[illegible]E+04  2.55E+02   0.9078      2.43E-14  2.96E-12  2.98E-12  3.69E-14   0.9918
0.750     0.093      5.16E+03  1.45E+05  1.50E+05  1.84E+03   0.9657      2.93E-07  4.12E-06  4.42E-06  5.09E-08   0.9325
1.000     0.112      1.49E+04  5.63E+05  5.78E+05  7.06E+03   0.9742      4.73E-04  2.72E-03  3.19E-03  3.96E-05   0.8516
1.250     0.125      3.29E+04  1.53E+06  1.57E+06  1.91E+04   0.9790      3.19E-02  1.21E-01  1.53E-01  1.91E-03   0.7909
1.500     0.137      6.17E+04  3.34E+06  3.40E+06  4.15E+04   0.9819      4.94E-01  1.54E+00  2.03E+00  2.54E-02   0.7567
1.750     0.146      1.03E+05  6.25E+06  6.35E+06  7.74E+04   0.9837      3.44E+00  9.82E+00  1.33E+01  1.66E-01   0.7403
2.000     0.150      1.60E+05  1.04E+07  1.06E+07  1.23E+05   0.9849      1.47E+01  4.12E+01  5.59E+01  7.00E-01   0.7368
2.250     0.166      2.32E+05  1.61E+07  1.63E+07  1.99E+05   0.9858      4.57E+01  1.31E+02  1.76E+02  2.21E+00   0.7409
2.500     0.176      3.21E+05  2.32E+07  2.35E+07  2.66E+05   0.9864      1.14E+02  3.41E+02  4.54E+02  5.69E+00   0.7497
```

```
Z1= 16
A1= 32.064
EI =   0.50000        EMAX=    2.50000        ESTEP=    0.25000

Z2= 70
A2= 173.040

J. A. BEARDEN AND A. F. BURR, REV. MOD. PHYS. 39, 125 (1967):  U1= 2398.1  U2= 2173.0  U3= 1950.   U4= 1576.3  U5= 1527.8

              THETA = 0 * U(EV) / Z2**2/13.605(EV) :        TH1= 0.4596  TH2= 0.4165  TH3= 0.3737  TH4= 0.4370  TH5= 0.4235

E. J. MCGUIRE, PHYS. REV. A5, 1043 (1972):
SUBSHELL FLUORESCENCE YIELDS                    1          2          3          4          5
                                          0.00115    0.00217    0.00152    [illegible]  0.0216

COSTER-KRONIG PROBABILITIES         S12    S13    S14    S15    S23    S24    S25    S34    S35    S45
                                  0.272  0.525  0.056  0.091  0.116  0.689  0.125  0.141  0.701  0.073

 Z1= 16     Z2= 70                              **** M-SHELL CROSS SECTIONS (CM**2) ****

                               FIRST BORN APPROXIMATION                                             ECPSS. CORR.
 EI(MEV)  KSI RELATIV.  DIRECT + CAPTURE = IONIZATION XRAY PROD.  C/I        DIRECT + CAPTURE = IONIZATION XRAY PROD.  C/I

  0.500       0.081      6.70E+02  6.59E+03  7.26E+03  1.11E+02   0.9069      1.59E-15  1.43E-13  1.45E-13  2.21E-15   0.9891
  0.750       0.097      3.26E+03  4.99E+04  5.23E+04  7.97E+02   0.9373      5.69E-08  5.97E-07  6.54E-07  1.00E-08   0.9130
  1.000       0.111      9.56E+03  1.94E+05  2.04E+05  3.15E+03   0.9551      1.45E-04  6.15E-04  7.60E-04  1.17E-05   0.8096
  1.250       0.124      2.13E+04  5.14E+05  5.65E+05  8.59E+03   0.9623      1.24E-02  3.45E-02  4.69E-02  7.21E-04   0.7359
  1.500       0.135      4.03E+04  1.22E+06  1.26E+06  1.91E+04   0.9660      2.22E-01  5.03E-01  7.25E-01  1.12E-02   0.6935
  1.750       0.146      6.90E+04  2.34E+06  2.41E+06  3.60E+04   0.9718      1.70E+00  3.51E+00  5.21E+00  8.03E-02   0.6737
  2.000       0.156      1.05E+05  4.03E+06  4.13E+06  6.27E+04   0.9745      7.84E+00  1.57E+01  2.35E+01  3.62E-01   0.6666
  2.250       0.166      1.54E+05  6.36E+06  6.52E+06  9.90E+04   0.9764      2.55E+01  5.20E+01  7.75E+01  1.20E+00   0.6710
  2.500       0.175      2.15E+05  9.42E+06  9.64E+06  1.46E+05   0.9777      6.63E+01  1.40E+02  2.07E+02  3.19E+00   0.6791
```

```
           Z1= 18
           M1= 39.950
           EMIN=    0.50000       EMAX=    2.50000       ESTEP=    0.25000

           Z2= 71
           M2= 175.000

 J. A. BEARDEN AND A. F. BURR, REV. MOD. PHYS. 39, 125 (1967): EM1= 2491.2  EM2= 2263.5  EM3= 2025.5  EM4= 1639.4  EM5= 1588.5
                 THETA = 9 * ...(Z2) / Z2 /13.605(Z1) :         TH1= 0.9616  TH2= 0.8194  TH3= 0.3750  TH4= 0.4364  TH5= 0.4229

 E. J. MCGUIRE, PHYS. REV. A5, 1043 (1972):
 SUBSHELL FLUORESCENCE YIELDS                                  W1           W2           W3           W4           W5
                                                          0.00153      0.00219      0.00152      0.01010      0.01603

 COSTER-KRONIG PROBABILITIES          S12    S13    S14    S15    S23    S24    S25    S34    S35    F45
                                    0.257  0.537  0.050  0.090  0.115  0.672  0.135  0.121  0.777  0.856

 Z1= 18    Z2= 71                                           **** M-SHELL CROSS SECTIONS (BARN) ****

                                    FIRST BORN APPROXIMATION                                        ECPSSR THEORY
                           ---------------------------------------------------------------------------------------------------------
 E1(MEV)   KSI RELATIV.    DIRECT + CAPTURE = IONIZATION XRAY PROD.   C/I          DIRECT + CAPTURE = IONIZATION XRAY PROD.   C/I
 ---------------------------------------------------------------------------------------------------------------------------------

  0.500      0.080       5.33E+02  3.94E+03  4.47E+03  7.65E+01  0.8809        3.68E-16  2.88E-14  2.92E-14  4.98E-16  0.9874
  0.750      0.097       2.60E+03  2.94E+04  3.20E+04  3.46E+02  0.9186        2.36E-08  2.17E-07  2.40E-07  4.11E-09  0.9016
  1.000      0.111       7.67E+03  1.18E+05  1.25E+05  2.15E+03  0.9388        7.67E-05  2.84E-04  3.61E-04  6.19E-06  0.7876
  1.250      0.123       1.72E+04  3.32E+05  3.50E+05  5.39E+03  0.9508        7.51E-03  1.81E-02  2.56E-02  4.40E-04  0.7062
  1.500      0.135       3.26E+04  7.53E+05  7.86E+05  1.34E+04  0.9586        1.46E-01  2.83E-01  4.29E-01  7.40E-03  0.6596
  1.750      0.145       5.52E+04  1.47E+06  1.52E+06  2.60E+04  0.9637        1.16E+00  2.08E+00  3.25E+00  5.60E-02  0.6382
  2.000      0.155       8.61E+04  2.55E+06  2.64E+06  4.51E+04  0.9673        5.59E+00  9.57E+00  1.52E+01  2.61E-01  0.6311
  2.250      0.165       1.25E+05  4.08E+06  4.20E+06  7.19E+04  0.9699        1.89E+01  3.25E+01  5.15E+01  8.86E-01  0.6324
  2.500      0.174       1.76E+05  6.10E+06  6.28E+06  1.07E+05  0.9720        5.00E+01  8.94E+01  1.39E+02  2.41E+00  0.6413
```

```
Z1= 13
A1= [illegible]
E1=   0.50000        EMAX=    2.50000        ESTEP=    0.25000

Z2= 72
A2= 17[illegible]

J. A. BEARDEN AND A. F. BURR, REV. MOD. PHYS. 39, 125 (1967): U1= [illegible]  U2= [illegible]  U3= [illegible]  U4= 1716.4  U5= 1661.7
             THETA = 4 * U(Z2) / Z1**2/13.605(Z2) :        TH1= [illegible]  TH2= [illegible]  TH3= [illegible]  TH4= [illegible]  TH5= 0.4051

E. J. MCGUIRE, PHYS. REV. A5, 1043 (1972):
SUBSHELL FLUORESCENCE YIELDS               W1          W2          W3          W4          W5
                                        [illegible] [illegible] [illegible] [illegible] [illegible]

COSTER-KRONIG PROBABILITIES          S12    S13    S14    S15    S23    S24    S25    S34    S35    F45
                                    0.222  0.593  0.201  0.107  0.115  0.674  0.106  0.102  0.794  0.434

 Z1= 13    Z2= 72                                        **** M-SHELL CROSS SECTIONS (BARN) ****

                          FIRST BORN APPROXIMATION                                          ECPSSR THEORY
 EI(MEV)  KSI RELATIV.  DIRECT + CAPTURE = IONIZATION XRAY PROD.  C/I          DIRECT + CAPTURE = IONIZATION XRAY PROD.  C/I

  0.500      0.080     4.03E+02  2.18E+03  2.59E+03  4.90E+01    0.8443        7.86E-17  5.22E-15  5.30E-15  9.94E-17    0.9851
  0.750      0.096     1.97E+03  1.63E+04  1.82E+04  3.45E+02    0.8957        9.27E-07  7.30E-06  8.22E-06  1.55E-07    0.8872
  1.000      0.110     5.91E+03  6.54E+04  7.14E+04  1.35E+03    0.9171        3.91E-05  1.24E-04  1.63E-04  3.07E-06    0.7596
  1.250      0.122     1.33E+04  1.87E+05  2.00E+05  3.78E+03    0.9356        4.38E-03  8.97E-03  1.33E-02  2.52E-04    0.6720
  1.500      0.133     2.53E+04  4.28E+05  4.53E+05  8.57E+03    0.9442        9.26E-02  1.52E-01  2.45E-01  4.64E-03    0.6215
  1.750      0.144     4.29E+04  8.43E+05  8.86E+05  1.67E+04    0.9516        7.86E-01  1.17E+00  1.96E+00  3.72E-02    0.5960
  2.000      0.154     6.72E+04  1.48E+06  1.55E+06  2.93E+04    0.9567        3.92E+00  5.60E+00  9.51E+00  1.81E-01    0.5882
  2.250      0.163     9.[illegible]E+04  2.40E+06  2.50E+06  4.73E+04    0.9605        1.36E+01  1.95E+01  3.31E+01  6.26E-01    0.5901
  2.500      0.172     1.36E+05  3.64E+06  3.78E+06  7.15E+04    0.9634        3.66E+01  5.47E+01  9.13E+01  1.73E+00    0.5992
```

```
                Z1= 18
                M1= 39.9[illegible]
                E1=    [illegible]        [illegible]=   [illegible]        [illegible]=   [illegible]

                Z2= 79
                M2= 197.0[illegible]

J. A. BEARDEN, A. F. BURR, REV. MOD. PHYS. 39, 125 (1967): U1= [illegible]   U2= [illegible]   U3= 27[illegible]   U4= 2291.1  U5= 2295.7
                THETA = [illegible] * E1(EV) / Z2[illegible] /13.605(EV) :        T1= [illegible]   T2= [illegible]   T3= [illegible]   T4= [illegible]529  T5= 0.4360

E. J. MCGUIRE, PHYS. REV. A5, 1043 (1972):
SUBSHELL FLUORESCENCE YIELDS                         1           2            3              4           5
                                              0.0213[illegible]   0.00123[illegible]   0.0[illegible]   .1[illegible]   0.[illegible]

COSTER-KRONIG PROBABILITIES          S12    S13    S14    S15    S23    S24    S25    S34    S35    S45
                                    0.169  0.59[illegible]  [illegible].127  [illegible].112  0.119  [illegible].671  0.095  [illegible].11[illegible]  [illegible].732  [illegible].9[illegible]

 Z1= 18    Z2= 79                           **** [illegible] CROSS SECTIONS ([illegible]) ****

                              FIRST BORN APPROXIMATION                                     ECPSSR THEORY
                     ---------------------------------------------------------------------------------------------------
 E1(MEV)  KSI RELATIV.  DIRECT + CAPTURE = IONIZATION XRAY PROD.  C/I          DIRECT + CAPTURE = IONIZATION XRAY PROD.  C/I
 ---------------------------------------------------------------------------------------------------------------------------

  0.500      0.077       6.71E+01  7.43E+01  1.41E+02  3.59E+00   0.5255        6.64E-22  1.03E-20  1.69E-20  4.61E-22   0.9608
  0.750      0.093       3.51E+02  5.30E+02  8.82E+02  2.39E+01   0.6015        8.14E-12  2.77E-11  3.58E-11  9.79E-13   0.7725
  1.000      0.105       1.[illegible]E+03  2.14E+03  3.2[illegible]E+03  8.69E+01   0.66[illegible]        2.57E-07  3.4[illegible]E-07  6.0[illegible]E-07  1.65E-08   0.5738
  1.250      0.117       2.54E+03  6.26E+03  8.8[illegible]E+03  2.36E+02   0.7118        8.3[illegible]E-05  7.06E-05  1.55E-04  4.24E-06   0.4579
  1.500      0.126       4.96E+03  1.49E+04  1.98E+04  5.31E+02   0.7592        3.38E-03  2.22E-03  5.60E-03  1.54E-04   0.3969
  1.750      0.137       8.64E+03  3.06E+04  3.93E+04  1.05E+03   0.7799        4.45E-02  2.55E-02  7.00E-02  1.92E-03   0.3643
  2.000      0.1[illegible]5       1.38E+04  5.66E+04  7.04E+04  1.98E+03   0.8[illegible]37        2.97E-01  1.60E-01  4.57E-01  1.26E-02   0.3506
  2.250      0.155       2.06E+04  9.63E+04  1.17E+05  3.11E+03   0.8227        1.29E+00  6.82E-01  1.96E+00  5.43E-02   0.3451
  2.500      0.163       2.93E+04  1.54E+05  1.83E+05  4.86E+03   0.8364        4.18E+00  2.22E+00  6.40E+00  1.76E-01   0.3467
```

```
           Z1= 18
           M1= 39.950
           [illegible]=   0.50000      EMAX=    2.50000      ESTEP=    0.25000

           Z2= 82
           M2= 207.200

 J. A. BEARDEN AND A. F. BURR, REV.MOD.PHYS. 39, 125 (1967): EM1= 3850.7  EM2= 3554.2  EM3= 3066.4  EM4= 2585.6  EM5= 2484.0

                 THETA = 9 * E1(EV) / 72? /13.6?(EV) :        TH1= [illegible]  TH2= 0.4677  TH3= [illegible]  TH4= 0.4619  TH5= 0.4436

 E. J. MCGUIRE, PHYS. REV. A5, 1043 (1972):
 SUBSHELL FLUORESCENCE YIELDS
                                                 [illegible]   [illegible]   [illegible]   [illegible]   [illegible]

 COSTER-KRONIG PROBABILITIES         S12    S13    S14    S15    S23    S24    S25    S34    S35    S45
                                    0.119  0.636  0.066  0.099  0.106  0.665  0.056  0.093  0.759  0.035

 Z1= 18     Z2= 82                              **** M-SHELL CROSS SECTIONS (BARN) ****

                          FIRST BORN APPROXIMATION                                                  ECPSSR THEORY
 E1(MEV)  KSI RELATIV.  DIRECT + CAPTURE = IONIZATION XRAY PROD.  C/I          DIRECT + CAPTURE = IONIZATION XRAY PROD.  C/I
 ------------------------------------------------------------------------------------------------------------------------------

  0.500      0.076      3.56E+01  2.09E+01  5.66E+01  1.61E+00   0.3694       2.56E-24  4.13E-23  4.39E-23  1.38E-24   0.9413
  0.750      0.091      1.63E+02  1.39E+02  3.02E+02  8.65E+00   0.4611       2.76E-13  6.88E-13  9.64E-13  3.05E-14   0.7139
  1.000      0.104      5.15E+02  5.58E+02  1.07E+03  3.03E+01   0.5200       2.34E-06  2.30E-06  4.64E-06  1.47E-07   0.4963
  1.250      0.115      1.22E+03  1.63E+03  2.85E+03  9.02E+01   0.5718       1.29E-05  7.90E-06  2.08E-05  6.60E-07   0.3795
  1.500      0.125      2.43E+03  3.89E+03  6.32E+03  2.06E+02   0.6157       7.16E-04  3.37E-04  1.05E-03  3.35E-05   0.3195
  1.750      0.134      4.27E+03  8.07E+03  1.23E+04  3.89E+02   0.6537       1.16E-02  4.72E-03  1.63E-02  5.19E-04   0.2889
  2.000      0.143      6.90E+03  1.50E+04  2.19E+04  6.92E+02   0.6856       9.01E-02  3.40E-02  1.24E-01  3.95E-03   0.2741
  2.250      0.151      1.04E+04  2.59E+04  3.63E+04  1.13E+03   0.7126       4.36E-01  1.60E-01  5.96E-01  1.90E-02   0.2681
  2.500      0.159      1.50E+04  4.18E+04  5.68E+04  1.79E+03   0.7355       1.54E+00  5.60E-01  2.10E+00  6.69E-02   0.2662
```

```
              Z1= 13
               = 35.0[illegible]
              [illegible]=   [illegible]          [illegible]=   [illegible]          [illegible]=   0.250[illegible]

              Z2= 53
               = 2[illegible]

J. [illegible]                                              [illegible]=   [illegible]   [illegible] 2687.5   [illegible]= 2570.6
              [illegible] = [illegible] / Z2[illegible] :     [illegible]= [illegible]  [illegible]= [illegible]  [illegible]= [illegible]  [illegible]= [illegible].0048  [illegible]= 0.4461

E. J. [illegible] (1972):
SAHRSCHEL [illegible]
                                   [illegible]   [illegible]    0.0533[illegible]   [illegible]   [illegible]

COSTER-KRONIG PROBABILITIES      512    513    514    515    523    524    525    534    535    545
                                 [illegible] 0.650  [illegible] [illegible] 0.113  [illegible] 0.003  [illegible] [illegible] 0.035

Z1= 13     Z2= 53                       **** [illegible] CROSS SECTIONS (BARN) ****

                          FIRST BORN APPROXIMATION                                        [illegible] THEORY
        -----------------------------------------------------------------------------------------------------
E1(MEV)  KSI RELATIV.  DIRECT + CAPTURE = IONIZATION XRAY PROD.  C/I        DIRECT + CAPTURE = IONIZATION XRAY PROD.  C/I
-------------------------------------------------------------------------------------------------------------

 0.500     0.075      2.36E+01  1.33E+01  3.71E+01  1.24E+00  0.3502      3.63E-25  5.21E-24  5.57E-24  1.83E-25  0.9340
 0.750     0.091      1.27E+02  9.24E+01  2.21E+02  7.29E+01  0.3296      4.46E-14  1.93E-13  2.77E-13  9.14E-15  0.6949
 1.000     0.103      4.06E+02  3.63E+02  7.70E+02  2.57E+01  0.3759      1.02E-09  9.15E-10  1.94E-09  6.46E-10  0.4719
 1.250     0.114      9.67E+02  1.03E+03  2.00E+03  6.77E+01  0.3265      6.80E-06  3.77E-06  1.06E-05  3.49E-07  0.3564
 1.500     0.124      1.93E+03  2.57E+03  4.50E+03  1.49E+02  0.3713      4.22E-04  1.79E-04  6.01E-04  1.99E-05  0.2984
 1.750     0.133      3.41E+03  5.33E+03  8.74E+03  2.49E+02  0.6150      7.34E-03  2.70E-03  1.00E-02  3.32E-04  0.2687
 2.000     0.142      5.53E+03  9.96E+03  1.55E+04  5.12E+02  0.5932      6.01E-02  2.04E-02  8.05E-02  2.67E-03  0.2536
 2.250     0.150      8.56E+03  1.72E+04  2.58E+04  3.66E+02  0.6722      3.03E-01  9.93E-02  4.02E-01  1.33E-02  0.2471
 2.500     0.156      1.21E+04  2.78E+04  3.99E+04  1.32E+03  0.3909      1.10E+00  3.53E-01  1.45E+00  4.84E-02  0.2451
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