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Review of Electron-Impact-Excitation
Cross Sections for Copper Atom

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Review of Electron Impact Excitation
Cross Sections for Copper Atom

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ABSTRACT

Excitation of atomic copper by electron impact plays an important role in the copper vapor laser and accurate cross sections are needed for understanding and modeling laser performance. During the past seven years, there have been several attempts to normalize the relative elastic and inelastic cross sections measured by Trajmar and coworkers. However, each of these efforts have yielded different cross sections, and the uncertainty in the correct normalization of the data has been a source of confusion and concern for the kinetic modeling efforts. This difficulty has motivated us to review previous work on the electron impact excitation of copper atom and to perform new calculations of the inelastic cross sections using the impact parameter method.

In this memorandum we review the previous attempts to normalize the experimental data and provide a critical assessment of the accuracy of the resulting cross sections. We also present new theoretical cross sections for the electron impact excitation of the $2S \rightarrow 2P^0$ and $2S \rightarrow 2D$ transitions in copper. When the experimental cross sections are renormalized to the results of the impact parameter calculations, they are a factor of three smaller than those published in the latest paper of Trajmar et. al. At impact energies above 60 eV the excitation cross sections obtained with the impact parameter method agree well with the results of the very recent, unpublished, close-coupling calculations of Henry. This agreement suggests that the present normalization of the experimental cross sections is probably the most reliable one obtained to date.

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I. Introduction

Because of their importance in understanding the performance of the copper vapor laser, the measurement and calculation of the electron impact excitation cross sections for atomic copper has received considerable attention. Various forms of these cross sections have been used in kinetic models of the laser at AVCO¹, JPL², and at LLNL.^{3,4} Leonard made an early attempt to study the copper vapor laser⁵ by estimating the cross sections with a purely classical, Gryzinski method. The later AVCO model employed cross sections based on the experimental results of Williams and Trajmar⁶, normalized to an impact parameter calculation. Winter and Cartwright⁷ had previously used Born theory to provide an alternative normalization of the Williams and Trajmar cross sections. Later calculations by Winter, Cartwright, and Wray⁸ attempted to normalize the electron impact cross sections by comparing to more accurate static exchange calculations of the elastic scattering cross section. These calculations assumed added significance after Trajmar, Williams, and Srivastava⁹ measured relative differential cross sections (DCS) for elastic scattering and for excitation of the $2D_{5/2}$, $2D_{3/2}$, and $2P_{3/2, 1/2}$ states of Cu as a function of impact energy. Previously it was necessary to normalize the experimental cross sections for each measured energy, whereas with the newer data the normalization could be accomplished by comparing to theory at a single energy, chosen so as to minimize the errors in the calculations. Independently, Trajmar et. al.^{2,9} also attempted to normalize the cross sections by matching the generalized oscillator strength (GOS), at zero momentum transfer, to the known optical oscillator strength of the $4s \rightarrow 4p$ resonance transition.

The uncertainty in the correct normalization of the inelastic cross sections has been a source of confusion and concern for the kinetic modeling efforts. The cross sections matched to the static exchange elastic scattering calculation⁷ were presumably the most accurate. However, recent models indicate that these may have been overestimated by a factor of 2-4.¹⁰ This uncertainty has motivated us to review the previous attempts to normalize the data and to perform new calculations of the $2S \rightarrow 2P$ inelastic cross section in order to improve the accuracy of the excitation cross sections available for copper.

The Born elastic and inelastic cross sections are discussed first along with the attempts to normalize the experimental results to the optical oscillator strength. Following this the extensive static exchange calculations are reviewed. Finally the new impact parameter calculations are used to provide a better normalization of the experimental cross sections.

II. Born Elastic and Inelastic Cross Sections

The first attempt to normalize the experimental electron scattering cross sections for copper was by Winter and Cartwright⁷ using the Born approximation for both the elastic and inelastic cross sections. It was assumed that at the higher impact energy, 60 eV, the Born approximation would be valid. The normalization was accomplished by comparing to the elastic cross section since this was thought to be somewhat less sensitive. The normalization at the lower energy, 20 eV, was obtained by comparing the results of Hertel and Ross¹¹ on the potassium atom to Born calculations and then using a similar rescaling for the Born cross sections of copper.

The calculations used the gaussian basis set of Wachters¹² to determine the ground state Hartree-Fock wavefunction. The excited 4p orbital was determined from an improved virtual orbital, IVO, calculation. The results for the integrated cross sections are given in Table 1. In the first paper of Williams and Trajmar,⁶ the elastic cross section for 20 eV incident energy was rescaled to $91 \text{ \AA}^2$, since the results for potassium indicated the experimental values were 75% of the Born calculations. The actual calculated value was $121 \text{ \AA}^2$. The $91 \text{ \AA}^2$ value was used by Williams and Trajmar⁶ to normalize the remaining cross sections at 20 eV. At 60 eV incident energy the unscaled value of $59 \text{ \AA}^2$ for the elastic cross section was used to normalize the experimental data.

The Born approximation can also be used to calculate the generalized oscillator strength, GOS,

$$f(K) = \frac{2\Delta E}{K^2} \left| \int \psi_n^*(\vec{r}) e^{i\vec{K} \cdot \vec{r}} \psi_i(\vec{r}) d\vec{r} \right|^2 \quad (1)$$

where ΔE is transition energy, $\Delta E = E_i - E_n$, and ψ_n and ψ_i are the wavefunctions of the final and initial states. The vector $\vec{K}$ is the momentum change of the incident electron.

In the limit of zero momentum change, expression (1) reduces to that for the optical oscillator strength,

$$f = \frac{2\Delta E}{3} \left| \int \psi_n(\vec{r}) \vec{r} \psi_i(\vec{r}) d\vec{r} \right|^2 \quad (2)$$

A calculation using Wachter's basis set for the ground $2S$ and excited $2P$ states of copper atom gave 1.257 for the optical oscillator strength. The Born calculations gave a GOS of 1.264 at zero momentum transfer and 100 eV incident energy. Both values are considerably larger than the measured optical f -value of 0.711 a.u. given by Corliss,¹³ indicating that the Born approximation is over estimating the electron scattering cross sections.

Using the expression for the GOS defined by Bethe¹⁴ in terms of the DCS, Trajmar et. al.⁹ attempted to normalize their cross sections by comparing the DCS derived from their measurements to the experimental optical oscillator strength. However Fig. 4 of their paper clearly illustrates that there is a large uncertainty in the extrapolation to zero momentum transfer. Table II gives the integrated elastic and inelastic cross sections obtained by Trajmar, Williams, and Srivastava¹⁵ normalizing the GOS to the optical f -value. The range of values reflects the large uncertainty in the extrapolation of the GOS to zero momentum transfer.

Due to the uncertainties in the GOS normalization and to the inherent errors in the Born calculations, more accurate static exchange calculations were carried out as described in the next section.

III. Static Exchange Elastic Scattering Cross Sections

The elastic cross sections were determined by solving numerically for the scattering wavefunction in the potential field of the ground state atom including the possibility of exchange. The ground state wavefunction for Cu was determined using the numerical Hartree-Fock code of C. Froese Fischer.¹⁶ The scattering solutions were calculated with the static exchange code of Bates¹⁷ after considerable modification to include higher partial waves.

If the scattering solution is expanded in a partial wave series

$$\phi_k = \sum_{lm} P_{kl} Y_{lm}(\Omega) , \quad (3)$$

where the continuum radial functions are normalized according to

$$P_{kl}(r) \xrightarrow{r \rightarrow \infty} \left(\frac{2k}{\pi}\right)^{1/2} r (\cos \delta_l^\pm j_l(kr) - \sin \delta_l^\pm n_l(kr)) , \quad (4)$$

then the total elastic cross section, Q , can be expressed in terms of the singlet and triplet phase shifts, $\delta_l^\pm$, as follows,

$$Q = \sum_l \pi/k^2 (2l+1) (3\sin^2 \delta_l^- + \sin^2 \delta_l^\pm) \quad (5)$$

The differential cross section is given by

$$I(\theta) = 3/4 |f^-(\theta)|^2 + 1/4 |f^+(\theta)|^2 \quad (6)$$

where

$$f(\theta) = \frac{1}{2ik} \sum_l (2l+1) (e^{2i\delta_l^\pm} - 1) P_l(\cos\theta) \quad (7)$$

Since the ground state of the copper atom has a single electron in an open shell s-orbital, the $l = 0$ partial wave of ϕ_k must be constrained to be orthogonal to this occupied s-orbital. The remaining partial waves are orthogonal by angular symmetry. The copper 4s Hartree-Fock orbital is quite deformable as shown by the large, $22 \text{ \AA}^3$, polarizability of the copper atom.¹⁸ The static exchange calculation reported here do not include the effects of target polarization, and, as will be shown, this leads to large differences between the calculated and experimental DCS at small angles.

The calculated phase shifts for the first ten partial waves are listed in Table III for incident energies of 6, 10, 20, 60, 100, 200, and 1000 eV. The partial wave convergence is good for the lower energies, but at 60 eV and above additional partial waves up to $l = 15$ were included to converge the cross sections. Figure 1 compares the integral cross sections given by the Born approximation and the static exchange calculation to the experimental elastic cross section normalized to the optical oscillator strength from Table II. The agreement is not good and the low energy static exchange cross section appears to be less accurate than the Born approximation. Of course the experimental values are not reliable due to the difficulty in normalizing the GOS to the optical oscillator strength. If the experimental cross sections were renormalized to the integral elastic cross section determined by the static exchange calculation at 60 eV, we would obtain $7.7 \times 10^{-16} \text{ cm}^2$. This is only 13% of the Born value at 60 eV and out of the range of the GOS normalized values given in Table II. The lack of target polarization in the static exchange calculations probably leads to an underestimation of the elastic cross sections. In order to investigate the accuracy of the static exchange approximation, the computed elastic DCS is compared to the measurements of Trajmar et. al.⁹ at 6, 10, 20, 60, and 100 eV in Figs. 2-6, respectively. In each case the agreement is good, except at small angles where the static exchange approximation underestimates the cross section due to the lack of target polarization. However the integrated cross sections are obtained by weighting the DCS by $\sin \theta$ and integrating over θ . Therefore the errors in the DCS at small angles should not contribute as strongly to the integral cross section.

Because of the good agreement between the measured and the calculated shapes of the DCS, the last cross sections published by Trajmar et. al.⁹ were normalized to the value of the static exchange DCS at 100 eV and at $\theta = 40^\circ$, which is $2.61 \times 10^{-16} \text{ cm}^2 \text{ sr}^{-1}$. Matching the experimental cross section to this value and integrating over θ gives $2.90 \times 10^{-15} \text{ cm}^2$ for the elastic cross section at 100 eV. The integrated static exchange cross section is only $9.4 \times 10^{-16} \text{ cm}^2$. At 60 eV incident energy, the integrated static exchange cross section is $7.7 \times 10^{-16} \text{ cm}^2$ compared to the normalized experimental value of

$2.39 \times 10^{-15} \text{ cm}^2$. The integrated static exchange cross sections are about a factor of 3 smaller at both energies. Normalizing the experimental data to the DCS calculated for 20 eV or 60 eV gives somewhat smaller normalization factors. The three possible normalizations (comparing the DCS at 100 eV at 60 eV, or at 20 eV) predict $2.39 \times 10^{-15} \text{ cm}^2$, $1.59 \times 10^{-15} \text{ cm}^2$, and $1.24 \times 10^{-15} \text{ cm}^2$, respectively, for the elastic cross section at 60 eV. The value for the highest incident energy was taken to be more accurate and published by Trajmar et al.⁹. However the lack of consistency seen at the various incident energies indicates this is not a particularly reliable approach.

IV. Impact Parameter Calculations

In an attempt to improve the normalization of the relative experimental cross sections, we performed a new calculation of the inelastic cross sections of the copper atom. We used the semiclassical impact parameter method to study the electron impact excitation of the $3d^{10} 4s^2 S_{1/2}$ state to both the upper laser levels $3d^{10} 4p^2 P_{1/2,3/2}$ and the metastable, lower laser levels $3d^9 4s^2 D_{3/2,5/2}$. In this approximation, the integrated cross section has the form:

$$\sigma_{n \leftarrow i} = \frac{1}{g_i} |M_{ni}^{(\lambda)}|^2 G(E, \Delta E_{ni}, R_0)$$

where $g_i^{-1} |M_{ni}|^2$ is the optical transition probability for the transition $i \rightarrow n$. The "dynamical" factor G depends on the collision energy E , the transition energy ΔE_{ni} and the minimum impact parameter R_0 . In the present work R_0 was determined by the requirement that the Born approximation and the impact parameter method give the same cross sections for the $4s \rightarrow 4p$ transition at a collision energy of 200 eV. The resulting value of R_0 , 3.1 bohr, is completely consistent with the expected radius of the copper atom. Figure 7 compares the Born and impact parameter cross sections.

The Born excitation cross section was calculated using a single configuration, SCF, wave function for the $4s$ ground state and an "improved virtual orbital", IVO, description of the $4p$ excited state as previously discussed in section II. Since these simple wave functions

gave an optical oscillator strength of 1.26 for the $4s \rightarrow 4p$ transition, compared to the value of 0.71 reported by Corliss¹³ or the latest experimental value of 0.65¹⁹, the Born cross section was not sufficiently reliable to normalize the experimental data. However, once the minimum impact parameter was determined, we calculated physically realistic excitation cross sections for the $2S_{1/2} \rightarrow 2P_{1/2}$ and $2P_{3/2}$ transitions using the experimental transition energies and oscillator strengths¹⁹ in the impact parameter formula (Eq. (1)). These results were added to obtain the total excitation cross section of the $3d^{10} 4p^2 P$ levels, shown by the solid curve in Fig. 7. The experimental data of Trajmar et. al.⁹ were then normalized to the computed cross section at 60 eV impact energy. Figure 7 also compares the renormalized experimental cross sections to the previous values. The present procedure yields cross sections for the $4s \rightarrow 4p$ transition which are approximately a factor of three smaller than before.

Since Trajmar and coworkers measured relative differential cross sections for both the $2S \rightarrow 2P$ and $2S \rightarrow 2D$ transitions, we can assume that their data for the metastable levels $3d^9 4s^2 2D_{3/2,5/2}$ should be renormalized by exactly the same factor as for the resonance transition. Figure 8 shows the renormalized cross sections for exciting the metastable levels from the ground state. In order to study the energy dependence of these cross sections theoretically we again employed the impact parameter method, appropriately modified for electric quadrupole transitions. We used the same minimum impact parameter as in the case of the $4s \rightarrow 4p$ transitions and adjusted the electric quadrupole moments of the $3d^{10} 4s^2 S \rightarrow 3d^9 4s^2 2D_{3/2,5/2}$ transitions so that the calculated and the experimental cross sections agreed at 60 eV impact energy. The resulting theoretical cross sections are shown in Fig. 8.

In comparing our final theoretical cross sections to the renormalized experimental data, two points should be noted. First, the dependences of the calculated and the experimental cross sections on electron energy are different even between 20 and 60 eV, where the agreement should be the best. This discrepancy, which is apparent for both the $2S \rightarrow 2P$ and the $2S \rightarrow 2D$ cross sections, is not well understood. One possible problem is the procedure used to integrate the measured differential cross sections (DCS). As the electron impact

energy increases, the DCS become strongly peaked in the forward direction ($\theta = 0^\circ$), and the small scattering angles contribute a larger portion of the total, integrated cross section. Since Trajmar et. al.⁹ made no measurements for scattering angles less than 20° , the extrapolation of the DCS to $0 < \theta < 20^\circ$ may have introduced large uncertainties in the integrated cross section at the higher collision energies.

We believe that the current theoretical cross sections are reliable for impact energies above 20 eV. However, because the assumptions underlying the semiclassical impact parameter method break down near threshold, the shapes and the magnitudes of the cross sections below 10 eV must still be considered uncertain. Only carefully performed close-coupling calculations²⁰ will be able to predict the near threshold behavior of the required excitation or deexcitation cross section for copper.

V. Conclusion

We have reviewed the previous attempts to normalize the experimental data of Trajmar et. al. These include Born calculations, comparison of the generalized oscillator strength to the optical oscillator strength, and static exchange calculations of the elastic cross section. We have presented new inelastic cross sections for the copper atom which were calculated with the impact parameter method.

The various cross sections are summarized in Tables IV-VI. The experimental data of Trajmar et. al.⁹ was renormalized once more by comparing to the impact parameter calculations at 60 eV incident energy, as described in the previous section. This appears to be the best normalization at the present time, as supported by the good agreement with the recent close-coupling calculations of Henry²⁰ at impact energies above 60 eV. In addition the impact parameter normalized elastic cross sections agree well with the static exchange integrated cross sections at 60 and 100 eV incident energies. This is consistent with the good agreement between the experimental and static-exchange DCS for these energies. The disagreement in the DCS at small angles may be overemphasized by inaccurate extrapolation of the experimental data

previously mentioned. It was this disagreement that prompted Trajmar et. al.⁹ to use the calculated DCS at 40 and 100 eV incident energy to normalize their data. In retrospect it would have been more accurate to use the integrated elastic cross section instead. The uncertain extrapolation and possibly inaccurate integration of the experimental DCS may explain the lack of agreement with the calculated static exchange integral cross sections.

References

1. D. Trainor, A. Mandl, and H. Hyman, Metal Vapor Visible Laser Kinetics Program Semi-Annual Report, AVCO Everett Research Laboratories Incorporated, March-August 1975.
2. G. Russel, Final Report Copper Laser Research, Jet Propulsion Laboratory, Pasadena, California, 1977.
3. J. L. Miller, Copper Vapor Laser Kinetics Model, UCID-18182 Lawrence Livermore National Laboratory, 1978.
4. B. Warner, private communication, Lawrence Livermore National Laboratory, 1980.
5. D. A. Leonard, IEEE J. Quant. Elect. 3, 380 (1976).
6. W. Williams and S. Trajmar, Phys. Rev. Lett. 33, 197 (1974).
7. N. Winter and D. Cartwright, unpublished calculations, The Aerospace Corporation, El Segundo, Cal. (1974).
8. N. Winter, D. Cartwright, and M. Wray, Proc. 9th Int. Conf. on Physics of Electron and Atomic Collisions, Vol. 2 (Seattle: University of Washington Press) Abstracts p. 1023.
9. S. Trajmar, W. Williams, and S. Srivastava, J. Phys. B. 10, 3323 (1977).
10. B. Warner, private communication, 1980.
11. I. V. Hertel and K. J. Ross, J. Phys. B. 2, 285 (1969).
12. A. J. H. Wachters, J. Chem. Phys. 32, 1033 (1970).
13. C. H. Corliss, J. Res. Nat. Bur. Stand., Sect. A 74, 781 (1970)
14. H. A. Bethe, Ann. Phys., Lpz 5, 325 (1930).
15. S. Trajmar, W. Williams, and S. Srivastava, private communication, 1977.
16. C. F. Fischer, Computer Phys. Commun. 4, 107 (1972).
17. G. N. Bates, Computer Phys. Commun. 8, 220 (1974).
18. R. R. Teachout and R. T. Pack, Atomic Data 3, 195 (1971).
19. For the impact parameter calculations the more recent value of 0.65 for the optical oscillator strength was used. A. Bielski, J. Quant. Spectrosc. Radiat. Transfer 15, 463 (1975).
20. R. Henry, private communication (1980).
21. E. Ormande, private communication (1974).

Figure Captions

- Fig. 1. Integral elastic cross sections for electron scattering from copper atom. The bars represent the range of experimental cross sections obtained by normalizing to the optical oscillator strength.
- Fig. 2. Comparison of the calculated static exchange DCS (solid line) and experimental DCS from Ref. 9 (dashed line) for 6 eV incident energy.
- Fig. 3. Comparison of the calculated static exchange DCS (solid line) and experimental DCS from Ref. 9 (dashed line) for 10 eV incident energy.
- Fig. 4. Comparison of the calculated static exchange DCS (solid line) and experimental DCS from Ref. 9 (dashed line) for 20 eV incident energy.
- Fig. 5. Comparison of the calculated static exchange DCS (solid line) and experimental DCS from Ref. 9 (dashed line) for 60 eV incident energy.
- Fig. 6. Comparison of the calculated static exchange DCS (solid line) and experimental DCS from Ref. 9 (dashed line) for 100 eV incident energy.
- Fig. 7. Comparison of excitation cross sections for Cu ($^2S + ^2P$).
- Fig. 8. Comparison of excitation cross sections for Cu ($^2S + ^2D$).

Table 1. Born Approximation Results for the Integrated Elastic and Inelastic Cross Sections of Copper Atom.

E_0 (eV)	$Q_{00} (\text{\AA}^2)$	$Q(^2P)(\text{\AA}^2)$	$Q(^2D)(\text{\AA}^2)$
6	214.2	31.2	0.29
10	172.7	31.3	0.21
20	121.1	23.6	0.11
60	58.9	11.9	0.04
100	39.4	8.3	

Table II. Integrated Cross Sections* for the Copper Atom
Normalized to the Optical Oscillator Strength.

E_0 (eV)	$Q_{00}(\text{\AA}^2)$	$Q(^2P)(\text{\AA}^2)$	$Q(^2D_{5/2})(\text{\AA}^2)$	$Q(^2D_{3/2})(\text{\AA}^2)$
6	250-400	44-69	5-8	4-6
10	136-550	31-125	9-35	6-27
20	18-31	15-26	0.37-0.6	0.25-0.42
60	12-125	7-94	0.07-0.8	0.05-0.55

*The range of values for each cross section at a given energy indicates the uncertainty in the normalization of the experimental data.

Table III. Static Exchange Phase Shifts for the Copper Atom.

$\delta_l^{\pm}$	l	$E(\text{ev})$						
		6	16	20	60	100	200	1000
δ_l^+	0	.04305	-.138872	-.448093	-1.2268	1.45674	.770143	-1.113328
	1	-.09200	.146319	.191798	0.30372	-.651164	-1.185621	.4617908
	2	-.06775	-.05849	-.021208	-.068547	-.1409305	-.2696585	-.8687188
	3	-.00848	.004804	.0914138	.447884	.69415	1.068241	1.3577
	4	-.00222	-.001215	.021878	.164537	.27243	.4597374	.8178729
	5	-.00044	-.000625	0.006597	.0785277	.1423276	.2533065	.4967712
	6	-.000064	-.000202	0.002154	.040859	.0824145	.1576281	.2817148
	7	-.0000022	-.0000412	0.000725	.022085	.0499036	.1039676	.1676279
	8	.0000019	.0000036	0.000250	.0121406	.0309949	.07123154	.07193286
	9	.0000005	.0000076	0.000088	.0067435	.0193854	.0493017	.02875191
δ_l^-	0	.70019	.2978709	-.2528678	-1.18467	1.47712	.7778342	-1.112502
	1	.87445	.685068	.376664	-.268512	-.63451	-1.179526	.4624064
	2	.16451	.185008	.1391933	-.030036	-.1238966	-.2640865	-.8680746
	3	.04647	.09707164	.200849	.488399	.7104	1.073608	1.358288
	4	.008767	.02499123	.0696794	.199402	.291553	.465625	.8185381
	5	.00172	.0067749	.0268154	.103432	.15928	.2600683	.4973399
	6	.00034	.001845	.010475	.057424	.0959253	.1643408	.2822141
	7	.000068	.0005093	0.004075	.032664	.06008097	.1101076	.1681145
	8	.000013	.000144	0.001574	.0187195	.03839363	.0765612	.0724427
	9	.000002	.0000408	0.000604	.010756	.02463535	.0537746	.0293026

Table IV. Comparison of Integral Cross Sections for Elastic Scattering.

E_0 (eV)	$Q_{00}(\text{\AA}^2)$				
	6	10	20	60	100
Reference 9	49.5	84.3	49.4	23.9	29.0
Reference 6			91	59	
Born	214.2	172.7	121.1	58.9	39.4
Static Exchange	44.1	17.6	5.7	7.7	9.4
Present Normalization	16.7	28.4	16.6	8.05	9.78

Table V. Comparison of Integral Cross Sections for $^2S \rightarrow ^2P$.

E_0 (eV)	$Q(^2P)(\text{\AA}^2)$				
	6	10	20	60	100
Reference 9	8.85	40.8	44.3	17.7	
Reference 6			77.2	36.5	
Reference 1	5.3	8.7	8.7	5.3	
Born	31.2	31.3	23.6	11.9	8.3
Henry (Ref. 20)	7.42	7.42	7.31	5.51	4.13
Present Normalization	2.98	13.7	14.9	5.96	4.19

Table VI. Comparison of Integral Cross Sections for $^2S \rightarrow ^2D$

E_0 (eV)	6	10	20	60
<hr/>				
	$Q(^2D)(\text{\AA}^2)$			
	<hr/>			
Reference 9	1.80	4.95	1.65	0.26
Reference 6			3.11	0.62
Reference 1	0.62	0.35	0.19	0.085
Ormande (Ref. 21)	0.4	0.16	0.04	
Born	0.29	0.21	0.11	0.04
Henry (Ref. 20)	0.76	0.35	0.13	0.034
Present Normalization	0.60	1.67	0.55	0.088
<hr/>				
	$Q(^2D_{5/2})(\text{\AA}^2)$			
	<hr/>			
Present Normalization	0.35	0.96	0.30	0.051
<hr/>				
	$Q(^2D_{3/2})(\text{\AA}^2)$			
	<hr/>			
Present Normalization	0.25	0.71	0.25	0.037

INTEGRAL ELASTIC CROSS SECTIONS FOR ELECTRON SCATTERING FROM COPPER ATOM

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

COMPARISON OF EXCITATION CROSS SECTIONS FOR $\text{Cu}(2s \rightarrow 2p)$

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Fig. 7

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Fig. 8