Atomic Data and Nuclear Data Tables **77,** 87–95 (2001)
doi:10.1006/adnd.2000.0847, available online at http://www.idealibrary.com on IDEAL®

ELECTRON IMPACT EXCITATION CROSS SECTIONS AND RATES FROM THE GROUND STATE OF ATOMIC CALCIUM

ANDY M. SAMSON and KEITH A. BERRINGTON

School of Science and Mathematics, Sheffield Hallam University, Sheffield S1 1WB, United Kingdom

New R-matrix calculations are presented for electron excitation of atomic calcium. The target state expansion includes 22 states: $4s^2\ ^1S$; $4snl\ ^{1,3}L$, where nl is $3d$, $4p$, $5s$, $5p$, $4d$ and $4f$; $3d4p\ ^{1,3}P$, D, F; and $4p^2\ ^3P$, ^1D, ^1S terms. The calculation is in LS coupling, and configuration interaction involving $3p$ subshell correlation is included. Electron impact excitation cross sections from the $4s^2$ ground state to the next 10 states are tabulated for low energies, and thermally averaged effective collision strengths are tabulated over a range of electron temperatures from 1000 to 10,000 K. Comparisons are made with previous cross sections calculations for the $4s^2$–$4s4p\ ^3P^o$ transition; excellent agreement is found with experimentally derived rates for $4s^2$–$4s4p\ ^1P^o$. © 2001 Academic Press

0092-640X/01 $35.00

CONTENTS

INTRODUCTION

Electron–atom collisions play a fundamental role in astrophysical and laboratory plasmas, coupling the electron gas to the radiation field through atomic excitations and deexcitations. Collision cross sections are therefore a crucial component in determining the state of matter from the observed radiation field, in investigations of the structure and evolution of galaxies, gas clouds, stars and other objects which can be studied spectroscopically. Particular applications include stellar atmospheres in cases where large deviations from local thermal equilibrium (LTE) may be present, such as in hot stars or in low-gravity high-luminosity stars. As a diagnostic, Ca I lines arising from the neutral calcium present in such cool stellar plasma can be used to estimate the abundance of Ca in galactic M giants, F supergiants, and other extragalactic red giants.

The allowed transition $4s^2$–$4s4p\ ^1P^o$ represents probably the most accurately known excitation cross section in Ca, due to measurements made at JILA [1, 2]. In these experiments the relative intensity of the resonance line of Ca I (422.7 nm) was obtained as a function of electron energy from threshold to 1000 eV, where the cross sections were normalized to the Born approximation. The overall accuracy is quoted as 10% after correcting for cascade contributions. Crandall et al. [2] presented these results as a simple fit to the rate coefficient as a function of electron temperature.

A recent theoretical calculation on electron–calcium collisions has been carried out by Yuan and Fritsche [3] using R-matrix techniques [4]. The main motivation for their work was to examine elastic scattering from the Ca ground state and photodetachment of Ca^-; however, they also presented cross sections for the inelastic transition $4s^2$–$4s4p\ ^3P^o$. They used a six-state model and an elaborate set of virtual orbitals optimized on these states, but did not include core (i.e., $3p$ subshell) correlation. As we shall see, this affects the energy position of the calculated excitation thresholds. After allowing for such energy shifts, the overall agreement with experiment [5, 6] for the elastic cross section was qualitatively good. Yuan [7] has just published a new five-state R-matrix calculation developing further the photodetachment work and now includes core correlation to improve the calculated energies.

The present work then can be seen to be an extension to the Yuan and Fritsche work, in which we aim to improve the representation of the excited states and to include more states in the target expansion, and hence to evaluate excitation cross sections and rates for a reasonable range of cool-star temperatures where neutral Ca is likely to be present.

The Calculation

We use the R-matrix programs of Berrington et al. [4], which solve the full-exchange many-electron Schrödinger equation in LS coupling within a spatial region centered on and enclosing the atom, and we use the variable phase method (VPM) [8] to solve the no-exchange coupled differential equations in the external region. (After finishing the calculation, a new external region program STGF by Badnell [9] became available for neutral targets: we find that it gives similar cross sections to VPM in our Ca runs in a fraction of the computer time, and we recommend the adoption of [9] in future work.)

We include 22 states in the target expansion, namely $4s^2\ ^1S$, $4snl\ ^{1,3}L$, where nl is $3d$, $4p$, $5s$, $5p$, $4d$ and $4f$, $3d4p\ ^{1,3}P$, D, F and $4p^2\ ^3P$, ^1D, ^1S terms. Bunge et al. [10] $1s$, $2s$, $2p$, $3s$, $3p$, $4s$ radial orbitals are used, and we optimized the $3d$, $4p$, $4d$, $4f$, $5s$, $5p$ orbitals on the $4snl$ triplet excited states using the CIV3 [11] atomic structure program. The radial wave functions are expressed as Slater-type orbitals in the form

$$P_{nl}(r) = \sum_j C_{jnl} r^{I_{jnl}} \exp(-\alpha_{jnl} r), \qquad (1)$$

with the orbital parameters tabulated in Table I.

Note that Yuan and Fritsche [3] used Clementi and Roetti [12] orbitals for $1s$, $2s$, $2p$, $3s$, $3p$, $4s$: these are not quite as accurate for Ca and lead to a Hartree–Fock ground state energy of -1353.4889 Ry as compared with -1353.4976 Ry from Bunge et al. (Incidentally, the correlation orbitals as given in Yuan and Fritsche's table 2 are not accurately normalized, with normalization integrals for $5p$, $4d$, and $5d$ out by more than 5%; this likely typographical error should not affect their results though, because of the normalization checks built into the standard R-matrix codes [4].)

The Ca^- binding energy is particularly sensitive to the wavefunction, so in Table A we show binding energies calculated by Yuan and collaborators [3, 7] as compared with our present result and that of experiment [13], showing good agreement when core correlation is included.

We include all configurations involving the outer two electrons in any of the excited orbitals, together with the following core excited configurations: $3p^5 3d^2 nl$, $3p^5 3d4snl$, $3p^4 3d^4$, $3p^4 3d^3 4s$, $3p^4 3d^3 4p$. The "$N+1$ electron" configuration terms are formed from these same configurations with the addition of one further electron. In the R-matrix programs [4] we set RA $= 50.4$ au and NRANG2 $= 12$. The latter refers to the number of continuum functions retained per scattering channel in the internal region wavefunction and was chosen such that the electron energy range of validity of our model due to the convergence of the R-matrix covers the threshold energy region of our model atom. We also include mass-correction and Darwin terms in our Hamiltonian

TABLE A

Comparison of the Ca^- $4s^2 4p$ Binding Energy (in meV) of Yuan and Fritsche [3] (without Core Correlation) and Yuan [7] and the Present Calculation (Both with Core Correlation) with Experiment [13]

	[3]	[7]	Present	Experiment [13]
Ca^-	75	29	33	24.55

TABLE B

Comparison of Ca Target State Energies (in eV) Calculated without [3] and with [7] $3p$ Core Correlation (cc) with Present Work and with Experiment [14]

			Present		[14]
State	Without cc [3]	With cc [7]	Without cc	With cc	Experiment
$4s4p\ ^3P^o$	1.804	1.885	1.680	1.805	1.886
$4s3d\ ^3D^e$	2.982	2.532	3.007	2.646	2.523
$4s3d\ ^1D^e$	3.047	2.743	3.029	2.815	2.709
$4s4p\ ^1P^o$	3.078	2.888	2.965	2.985	2.932
$4s5p\ ^1P^o$	4.584	—	4.477	4.590	4.554

[4]. Table II gives the threshold energies in our model, compared with experiment [14]. Because our calculation is in LS coupling, we give the weighted average experimental energy arising from each triplet state in Table II.

In order to study the effects of core correlation, we show in Table B the energies of the five excited target states included by Yuan and Fritsche [3], who did not include core correlation but included correlation orbitals up to $6s$, $6p$, $6d$, and $4f$. Yuan and Fritsche had optimized on the ground and these five excited states, whereas our excited orbitals are all spectroscopic. Apart from the $4s4p\ ^3P^o$ state, the energies of Yuan and Fritsche agree well with our frozen core calculation. The improvement obtained by including $3p$ core correlation brings some of our calculated energies much closer to experiment: for example $4s3d\ ^3D^e$ improves from a 20% difference to 5%. Yuan's latest calculation [7] also finds marked improvement over [3] due to core correlation, as is shown in Table B.

As a further indication of the accuracy of the wavefunction, we note in Table C that our calculated oscillator strength shows excellent agreement with experiment [15] for the $4s^2$–$4s4p\ ^1P^o$ transition, but rather poor agreement for $4s^2$–$4s5p\ ^1P^o$, and this will affect the accuracy of the high-energy behavior of our corresponding cross section. As [3] and [7] do not quote their calculated f-values, we compare our results in Table C with the multiconfigurational Hartree–Fock (MCHF)

TABLE C

Comparison of Present Oscillator Strengths for Allowed Transitions from the Ca Ground State Calculated in Length (L) and Velocity (V) Form with MCHF Values [16] and Experiment [15]

Transition	Present		Vaeck et al.	Experiment
$^1S^e$–$^1P^o$	L	V	[16]	[15]
$4s^2$–$4s4p$	1.76	1.46	1.89	1.75
$4s^2$–$4s5p$	0.0045	0.0030	0.0173	0.0009
$4s^2$–$3d4p$	0.105	0.050	—	—

values of Vaeck et al. [16]; these authors showed that core correlation does not significantly affect the f-values.

We found it difficult to improve the accuracy of the wavefunction in relation to all aspects of what is shown in Tables A–C and Table II; our calculation is a compromise between a reasonably accurate representation of a number of excited states, and a computationally tractable number of orbitals and configurations in the expansions. An inspection of Table II indicates that the lower $4snl$ states and the two lowest $3d4p$ states are the most accurately represented out of the 22 states included, and indeed the energy ordering of our states is not correct above state 11; thus we restrict our further data tabulations to the lowest 11 states.

Results and Discussion

Figure 1 illustrates the excitation cross sections from the ground state to the first four excited states. Comparisons are made with previous cross section calculations for the $4s^2$–$4s4p\ ^3P^o$ forbidden transition, where we see broad agreement with Yuan and Fritsche [3], and we defer to these authors for an explanation of the main resonance features. An early close-coupling calculation by Fabrikant [17] is also shown, but that calculation suffered from the use of a model potential. Table III tabulates the cross section for electron excitation from the ground state of Ca as a function of electron energy, covering the low-energy range with a sufficient number of points to enable the main cross section features to be delineated.

The upper bound on our energy range is determined not only by NRANG2, as explained in the previous section, but also by the presence of pseudoresonances caused by the large amount of correlation in our wavefunction: this gives rise to

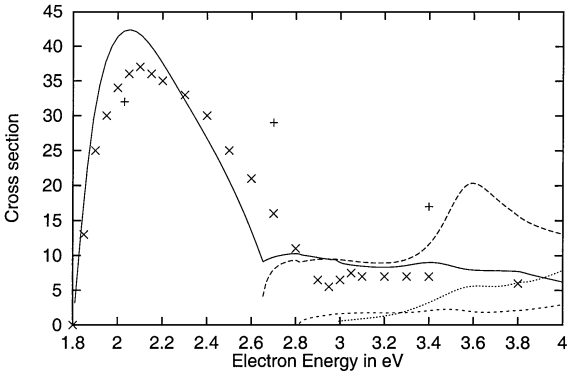

FIG. 1. Electron impact excitation cross sections in units of πa_0^2 from the present R-matrix calculation. Transitions are from the Ca $4s^2\ ^1S^e$ ground state to —, $4s4p\ ^3P^o$; – – –, $4s3d\ ^3D^e$; - - -, $4s3d\ ^1D^e$; . . . , $4s4p\ ^1P^o$. ×, calculation of Yuan and Fritsche [3] and +, calculation of Fabrikant [17], for $4s4p\ ^3P^o$.

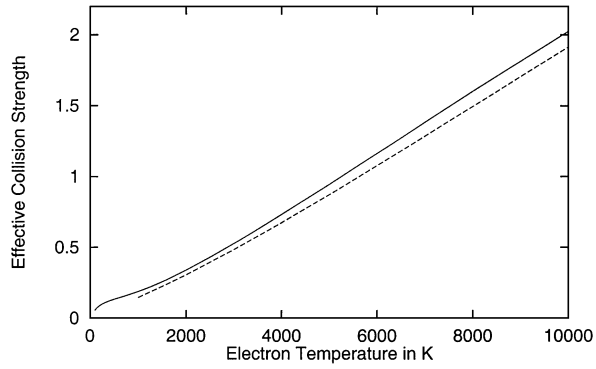

FIG. 2. Effective collision strength for Ca $4s^2\ ^1S^e$–$4s4p\ ^1P^o$. —, present R-matrix calculation; – – –, experiment [1, 2].

unphysical oscillations in our cross sections at energies above the highest threshold and restricts the validity of our method to lower energies.

The *effective collision strength* Υ for a given transition is calculated by integrating over the Maxwellian weighted collision strength using the procedure of Burgess and Tully [18]. In order to carry out the integration, we assume the collision strength is constant at energies above the highest energy tabulated in Table III for a given transition. We can estimate the error in our calculated Υ due to this assumption by recalculating the integral with a zero high-energy collision strength for the forbidden transitions or with a monotonic extrapolation from the highest energies for the E1 and E2 transitions. The difference in the resulting Υ ranges from 0% for 1000 K to 10% at 10,000 K, the highest temperature we consider. The larger error is for the highest transitions, and although at these temperatures the effective collision strength is still dominated by the low-energy cross section, we note from Table C that for transition 1–11 our calculation overestimates the f-value (and therefore the high-energy behavior of the cross section), so that we expect our results for 1–11 to be the least accurate.

The excitation rate coefficient q_{ij} at electron temperature T (in K) from lower level i to upper level j is given in terms of Υ by

$$q_{ij} = 8.6291 \times 10^{-6} \frac{\Upsilon_{ij}}{g_i \sqrt{T}} \exp(-\Delta E / kT)\ \mathrm{cm}^3\ \mathrm{s}^{-1}, \quad (2)$$

where g_i is the statistical weight of the lower level. Figure 2 illustrates the effective collision strength for the $4s^2$–$4s4p\ ^1P^o$ transition, where excellent agreement is seen with experimentally derived rates from Crandall et al. [2] (our results are ∼5% higher, but their experimental error is 10%).

Table IV tabulates effective collision strengths for electron temperatures 1000–10,000 K for transitions from the

ground state. From the discussions above we estimate their accuracy to be ∼5%, but with a possiblity of errors exceeding 10% for the highest transitions and the highest temperatures.

References

1. V. Ehlers and A. Gallagher, Phys. Rev. A **7**, 1573 (1973)
2. D. H. Crandall, G. H. Dunn, A. Gallagher, D. G. Hummer, C. V. Kunasz, D. Leep, and P. O. Taylor, Astrophys. J. **191**, 789 (1974)
3. J. Yuan and L. Fritsche, Phys. Rev. A **55**, 1020 (1997)
4. K. A. Berrington, W. Eissner, and P. H. Norrington, Comput. Phys. Commun. **92**, 290 (1995)
5. N. I. Romanyuk, O. B. Shpenik, and I. P. Zapesochyi, Pis'ma Zh. Eksp. Teor. Fiz. **32**, 472 (1980) [JETP Lett. **32**, 452 (1980)]
6. N. I. Romanyuk, O. B. Shpenik, F. F. Papp, I. V. Chernysheva, I. A. Mandi, V. A. Kelemen, E. P. Sabad, and E. Yu. Remeta, Ukr. Fiz. Zh. **37**, 1639 (1992)
7. J. Yuan, Phys. Rev. A **61**, 012704 (2000)
8. J. P. Croskery, N. S. Scott, K. L. Bell, and K. A. Berrington, Comput. Phys. Commun. **27**, 385 (1982)
9. N. R. Badnell, J. Phys. B: At. Mol. Opt. Phys. **32**, 5583 (1999)
10. C. F. Bunge, J. A. Barrientos, and A. V. Bunge, Atomic Data and Nuclear Data Tables **53**, 113 (1993)
11. A. Hibbert, Comput. Phys. Commun. **9**, 141 (1975)
12. E. Clementi and C. Roetti, Atomic Data and Nuclear Data Tables **14**, 177 (1974)
13. V. V. Petrunin, H. H. Andersen, P. Balling, and T. Andersen, Phys. Rev. Lett. **76**, 744 (1996)
14. J. R. Fuhr and W. L. Wiese (1998), *Handbook of Chemistry and Physics*, 79th ed.; also see http://physics.nist.gov/
15. W. L. Wiese and G. A. Martin, in *Wavelengths and Transition Probabilities for Atoms and Atomic Ions* (Part II), edited by J. Reader, C. Corliss, W. L. Wiese, and G. A. Martin (NSRDS, US Department of Commerce, 1980); also see http://physics.nist.gov/
16. N. Vaeck, M. Godefroid, and J. E. Hansen, J. Phys. B: At. Mol. Opt. Phys. **24**, 367 (1991)
17. I. I. Fabrikant, *Atomniye Protsessi* (Zinatne, Riga, 1975), p. 80 [in Russian]
18. A. Burgess and J. A. Tully, Astron. Astrophys. **254**, 436 (1992)

EXPLANATION OF TABLES

TABLE I. Orbital Parameters of the Radial Wave Functions for Ca

The Slater-type orbital parameters of Eq. (1) are defined for each one-electron orbital nl in three rows of this Table. The first row contains the I_{jnl} powers of r for the nl orbital; the next rows give

α	The corresponding exponents
C	The corresponding coefficients

TABLE II. Target State Energies (in eV) for the Model Atom

This Table shows the target energy thresholds in eV relative to the ground state of Ca.

Index	The numeral used to represent a particular state
State	Configuration and term of the *LS* state
Present	Present calculation
Experiment	Reference data from http://physics.nist.gov/ [14]

TABLE III. Excitation Cross Sections from the Ground State of Ca

The cross sections are presented in units of πa_0^2.

E	The scattered electron energy in eV relative to the excitation threshold
$1–j$	The excitation cross section from the ground state to state j as indexed in Table II

TABLE IV. Effective Collision Strengths for Transitions from the Ground State of Ca

This Table presents the effective collision strengths Υ as a function of electron temperature in Kelvin.

$1–j$	The effective collision strength from the ground state to state j as indexed in Table II; the corresponding row presents Υ for each temperature for the given transition

In order to calculate the excitation rate coefficients, one can substitute Υ into Eq. (2) using for ΔE the experimental energies given in Table II. For example, the excitation rate for the 1–5 transition ($4s^2\ {}^1S^{\mathrm{e}}$–$4s4p\ {}^1P^{\mathrm{o}}$) at $T = 3000$ K is $8.6291 \times 10^{-6} \times 0.5268 \times \exp(-2.932/(0.00008617 \times 3000))/\sqrt{3000} = 0.9847 \times 10^{-12}$ cm^3 s^{-1}.

TABLE I. Orbital Parameters of the Radial Wave Functions for Ca

See page 92 for Explanation of Tables

	Slater-type parameters						
$3d$	r^3	r^3	r^3	r^3			
α	.6139192	1.3328319	3.0601373	6.8737316			
C	.0426562	.4870865	5.2717729	10.3943011			
$4p$	r^2	r^2	r^3	r^4	r^4		
α	1.2922328	8.0191695	1.3022345	.8244935	4.0021400		
C	-1.1683239	16.7151658	.6374261	.0391032	-2.8995315		
$4d$	r^3	r^4	r^4				
α	1.6163065	.3199395	2.1384211				
C	-2.2382781	.0006497	2.4183892				
$4f$	r^4						
α	.2555718						
C	.00024						
$5s$	r^1	r^2	r^3	r^4	r^5	r^4	r^3
α	8.5093784	2.6555151	.3494924	7.9662640	1.3721986	4.1894773	.7595431
C	-1.3364386	8.5000953	-.0120240	-225.5899949	.0607602	-41.3973986	.0239309
$5p$	r^2	r^3	r^4	r^5	r^5		
α	2.3134009	3.1645416	.9783378	.4264147	4.9557946		
C	4.0333963	-16.1796665	.0374770	-.0002261	28.8827799		

TABLE II. Target State Energies (in eV) for the Model Atom

See page 92 for Explanation of Tables

Index	State	Present	Experiment
1	$4s^2\ ^1S^e$	0.0	0.0
2	$4s4p\ ^3P^o$	1.805	1.892
3	$4s3d\ ^3D^e$	2.646	2.524
4	$4s3d\ ^1D^e$	2.815	2.709
5	$4s4p\ ^1P^o$	2.985	2.932
6	$4s5s\ ^3S^e$	4.017	3.910
7	$4s5s\ ^1S^e$	4.246	4.131
8	$3d4p\ ^3F^o$	4.467	4.442
9	$3d4p\ ^1D^o$	4.492	4.443
10	$4s5p\ ^3P^o$	4.556	4.533
11	$4s5p\ ^1P^o$	4.590	4.554
12	$4p^2\ ^3P^e$	4.661	4.774
13	$4s4d\ ^3D^e$	4.815	4.681
14	$4s4d\ ^1D^e$	4.826	4.624
15	$3d4p\ ^3D^o$	5.094	4.740
16	$4s4f\ ^1F^o$	5.219	5.250
17	$3d4p\ ^3P^o$	5.234	4.877
18	$4s4f\ ^3F^o$	5.242	5.228
19	$3d^2+4p^2\ ^1D^e$	5.331	5.048
20	$3d^2+4p^2\ ^1S^e$	5.386	5.181
21	$3d4p\ ^1F^o$	5.997	5.026
22	$3d4p\ ^1P^o$	6.487	5.447

TABLE III. Excitation Cross Sections from the Ground State of Ca

See page 92 for Explanation of Tables

E eV	1–2	*E* eV	1–3	*E* eV	1–4	*E* eV	1–5	*E* eV	1–6
.004	3.14	.007	4.11	.001	.201	.008	.537	.010	.425
.032	13.3	.020	6.08	.015	.639	.021	.614	.024	.372
.059	22.5	.034	7.08	.028	.820	.157	1.06	.037	.365
.086	29.5	.047	7.73	.042	.948	.212	1.29	.051	.381
.113	34.4	.075	8.53	.069	1.14	.253	1.52	.064	.414
.141	37.7	.115	9.13	.123	1.42	.293	1.83	.078	.467
.168	40.0	.156	9.31	.178	1.64	.348	2.38	.092	.544
.222	42.2	.170	9.06	.273	1.76	.429	3.45	.105	.656
.277	42.1	.292	9.50	.464	1.78	.552	5.22	.119	.821
.358	39.3	.415	9.18	.532	1.90	.593	5.55	.132	1.07
.630	24.7	.551	8.94	.640	2.25	.661	5.61	.146	1.42
.739	17.7	.632	9.25	.681	2.27	.742	5.63	.160	1.85
.794	13.7	.687	9.90	.722	2.18	.824	6.16	.173	2.20
.848	9.11	.741	11.2	.804	1.88	.892	6.48	.187	2.29
.916	9.93	.782	12.7	.844	1.85	1.00	7.72	.200	2.09
.998	10.3	.836	15.7	.899	1.92	1.03	7.99	.214	1.79
1.16	9.40	.891	18.9	1.02	2.21	1.04	7.66	.228	1.62
1.17	9.41	.932	20.2	1.13	2.67	1.07	8.34	.241	1.34
1.20	8.92	.972	20.2	1.20	3.07	1.16	9.74	.268	1.58
1.32	8.40	1.19	14.9	1.32	3.65	1.20	9.69	.282	1.64
1.45	8.41	1.33	13.3	1.39	3.94	1.23	9.72	.296	1.64
1.60	9.02	1.37	13.0	1.44	4.20	1.25	9.94	.323	1.53
1.66	8.78	1.39	12.6	1.48	4.42	1.26	10.4	.432	.917
1.77	8.00	1.50	12.5	1.58	5.36	1.30	10.9	.459	.814
2.00	7.70	1.54	12.4	1.67	5.92	1.54	12.1	.473	.787
2.21	6.08	1.60	11.6	1.73	6.00	1.56	12.3	.486	.787
2.22	6.12	1.84	11.6	1.76	5.35	1.57	12.9	.500	.828
2.32	5.27	1.88	11.2	1.78	5.06	1.61	13.0	.513	.941
2.36	4.88	1.90	10.8	1.88	4.99	1.65	13.4	.527	1.21
2.37	4.88	1.91	10.2	1.99	5.11	1.74	13.1	.541	1.13
2.41	5.46	1.92	10.7	2.04	5.04	1.89	14.2	.554	.607
2.44	5.44	1.94	10.8	2.20	4.64	1.99	13.9	.568	.679
2.45	5.06	1.95	11.4	2.31	4.69	2.14	12.7	.595	.554
2.48	4.69	2.16	10.9	2.45	5.07	2.23	12.9	.609	.532
2.51	4.62	2.18	10.5	2.59	4.97	2.36	13.8	.622	.524
2.67	5.61	2.41	9.91	2.63	4.93	2.46	14.7	.636	.530
2.73	5.68	2.55	8.74	2.76	4.89	2.59	15.7	.677	.594
2.74	5.60	2.62	7.84	2.90	4.92	2.73	16.5	.772	.620
2.75	5.67	2.67	7.52	3.03	4.91	2.86	17.2	.799	.584
2.77	5.39	2.73	7.55	3.17	4.86	3.00	17.8	.826	.454
2.78	5.34	2.80	7.37	3.31	4.85	3.14	18.5	.867	.413
2.81	5.01	2.93	7.02	3.44	4.97	3.27	19.1	.949	.426
2.90	4.68	3.07	6.40	3.58	5.03	3.41	19.7	1.18	.494
2.98	4.78	3.20	5.60	3.72	5.12	3.44	19.8	1.22	.515
3.01	4.69	3.34	5.86	3.85	5.52	3.47	19.9	1.32	.586
3.04	4.71	3.48	6.30	3.87	5.64	3.50	20.0	1.83	.514
3.24	4.06	3.61	6.35	3.89	5.76	3.54	20.1	1.97	.392
3.36	3.59	3.75	6.26	3.91	5.89	3.58	20.2	2.51	.200

TABLE III. Excitation Cross Sections from the Ground State of Ca

See page 92 for Explanation of Tables

E eV	1–7	*E* eV	1–8	*E* eV	1–9	*E* eV	1–10	*E* eV	1–11
.012	.337	.010	.024	.024	.027	.001	.728	.008	.491
.026	.602	.050	.105	.038	.049	.015	1.25	.022	.541
.040	.991	.064	.130	.052	.073	.029	1.15	.090	.638
.053	1.43	.078	.152	.065	.096	.042	.893	.117	.676
.067	1.80	.091	.195	.079	.137	.056	.977	.130	.684
.080	2.06	.105	.267	.093	.189	.097	1.04	.130	.684
.094	2.23	.118	.330	.106	.176	.124	1.13	.226	.612
.121	2.44	.132	.354	.120	.176	.151	1.23	.239	.519
.162	2.57	.146	.388	.256	.336	.178	1.24	.253	.518
.203	2.57	.200	.573	.310	.408	.205	1.21	.294	.486
.230	2.47	.227	.636	.351	.481	.246	1.28	.335	.483
.257	2.21	.282	.718	.501	.594	.260	1.43	.457	.525
.271	2.00	.336	.848	.569	.608	.273	1.29	.579	.509
.284	1.69	.363	1.02	.596	.595	.287	1.31	.634	.499
.298	1.27	.445	1.38	.610	.568	.396	1.20	.647	.485
.312	1.42	.513	1.77	.650	.387	.559	1.11	.661	.441
.325	1.91	.622	2.48	.705	.204	.641	1.05	.688	.403
.339	1.92	.690	2.73	.746	.112	.654	1.06	.743	.367
.353	1.62	.771	2.86	.773	.085	.695	1.01	.852	.420
.461	1.24	.839	2.80	.800	.092	.763	1.04	.988	.478
.570	1.05	.975	2.56	.827	.117	.886	.973	1.23	.586
.584	1.15	1.11	2.47	.841	.153	1.02	.903	1.37	.659
.625	1.09	1.25	2.45	.854	.147	1.16	.833	1.42	.728
.774	1.10	1.38	2.36	.950	.133	1.29	.788	1.45	.690
.856	1.02	1.52	2.09	1.22	.096	1.43	.794	1.72	.734
1.09	.706	1.66	1.86	1.36	.197	1.57	.716	1.86	.793
1.13	.718	1.79	1.71	1.49	.326	1.70	.747	1.91	.855
1.88	1.10	1.93	1.52	1.77	.382	1.84	.804	1.94	.833
2.15	1.04	2.06	1.35	2.04	.518	1.97	.740	2.10	1.02

TABLE IV. Effective Collision Strengths for Transitions from the Ground State of Ca

See page 92 for Explanation of Tables

1–*j*	Electron temperature *T*(K)								
	1000	2000	3000	4000	5000	6000	7000	8000	10000
1–2	3.201	4.183	4.440	4.437	4.340	4.211	4.075	3.943	3.701
1–3	1.472	1.723	1.926	2.118	2.288	2.433	2.552	2.649	2.789
1–4	.2312	.2972	.3471	.3982	.4536	.5124	.5730	.6342	.7553
1–5	.1879	.3393	.5268	.7315	.9455	1.165	1.388	1.613	2.068
1–6	.2065	.2867	.3051	.3048	.2990	.2917	.2844	.2776	.2661
1–7	.4552	.5369	.5394	.5269	.5129	.5005	.4903	.4820	.4699
1–8	.0747	.1745	.2761	.3622	.4300	.4819	.5211	.5506	.5889
1–9	.0410	.0729	.0896	.0977	.1024	.1059	.1090	.1122	.1190
1–10	.3644	.3888	.3979	.4002	.3996	.3974	.3945	.3913	.3846
1–11	.1850	.1939	.1952	.1977	.2028	.2104	.2198	.2304	.2533