Atomic structure of the carbon like ion Ca XV

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- **Introduction (Ca XV ion)**
- The Hartree-Fock Relativistic (HFR) theory

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We can obtain ionized calcium by many approaches, for example, Tokamaks or the solar flare plasma which contain Extreme Ultra-Violet (XUV) solar emission lines of highly ionized calcium.

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$$\left[\sum_{i=1}^{N}\left(-\frac{1}{2}\nabla_{r_i}^2-\frac{Z}{r_i}\right)+\sum_{i<j=1}^{N}\frac{1}{r_{ij}}\right]\Psi(q_1,q_2,\ldots,q_N)$$
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The N-electron wavefunction used is the Slater Determinant:

$$\Psi(q_1, q_2, \ldots, q_N) = \frac{1}{\sqrt{N!}} \begin{vmatrix} u_\alpha(q_1) & u_\beta(q_1) & \cdots & u_\nu(q_1) \\ u_\alpha(q_2) & u_\beta(q_2) & \cdots & u_\nu(q_2) \\ \vdots & \ldots & \ldots & \vdots \\ u_\alpha(q_N) & u_\beta(q_N) & \cdots & u_\nu(q_N) \end{vmatrix}$$

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$$- \left[\sum_\mu \int u^*_\mu(q_j)\frac{1}{r_{ij}} u_\lambda(q_j) dq_j\right] u_\lambda(q_i) = E_\lambda u_\lambda(q_i); \lambda, \mu = \alpha, \beta, \ldots, \nu$$

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The Cowan atomic structure code (2018)

We used the first eight configurations of Ca XV:

$2s^2\ 2p^2$

$2s^2\ 2p\ 3p$

$2s^2\ 2p\ 4p$

$2s\ 2p^3$

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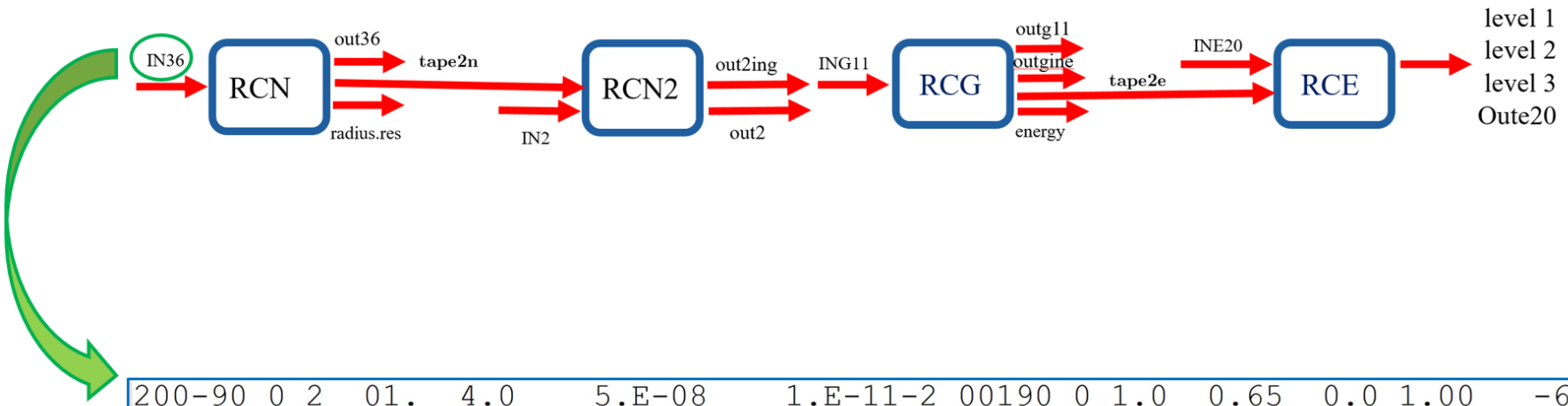


```
200-90 0 2  01.  4.0     5.E-08     1.E-11-2 00190 0 1.0  0.65  0.0 1.00   -6
   20     1Ca XV 2s22p               2s2 2p2
   20     1Ca XV 2p 3p               2s2 2p 3p
   20     1Ca XV 2p 4p               2s2 2p 4p
   20     1Ca XV 2s2p3               2s 2p3
   20     1Ca XV 2p 3s               2s2 2p 3s
   20     1Ca XV 2p 4s               2s2 2p 4s
   20     1Ca XV 2p 5s               2s2 2p 5s
   20     1Ca XV 2p 3d               2s2 2p 3d
   -1
```

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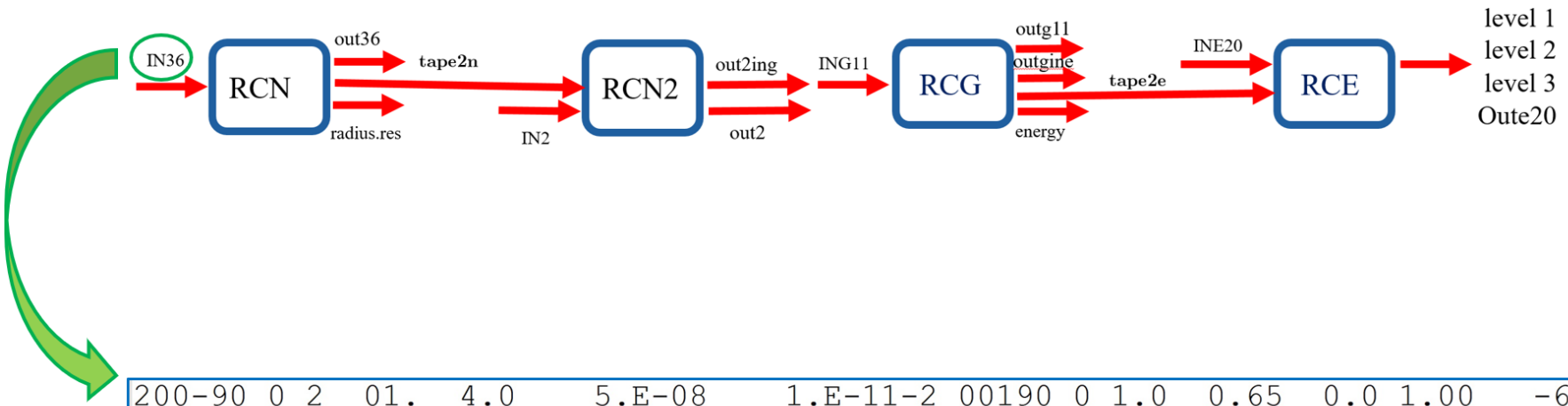


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   20     1Ca XV 2s2p3               2s 2p3
   20     1Ca XV 2p 3s               2s2 2p 3s
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   20     1Ca XV 2p 5s               2s2 2p 5s
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   -1
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```
G5INP  0 10 0 0.00002          0011111 1 00000000  9499949494 5.00    1 07200  0.0
       -1
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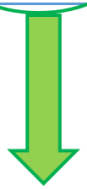

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The Slater scalings for highly ionized

94% | 99% | 94% | 94% | 94 %

- F^K the radial integration between equivalent electrons
- ξ_{nl} the Spin-orbit parameters
- F^K the radial integration between nonequivalent electrons
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"Energy levels for the configuration $2s^2\ 2p^2$ of Ca XV."

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$2s^2\ 2p^2$	^3P	2	35923	35171	35920
$2s^2\ 2p^2$	^1D	2	108600	104491	108736
$2s^2\ 2p^2$	^1S	0	197670	214620	197839
				4.3%	0.1%

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$2s\ 2p^3$	$^3D^o$	1	497570	529652	497632
$2s\ 2p^3$	$^3P^o$	1	582780	607890	582942
$2s\ 2p^3$	$^3P^o$	2	585670	611053	585800
$2s\ 2p^3$	$^3P^o$	0	581730	606177	581886
$2s\ 2p^3$	$^3D^o$	2	729650	759011	730043
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$2s^2\ 2p3s$	$^3P^o$	2	-	4428144	4115926
$2s^2\ 2p3s$	$^1P^o$	1	-	4441352	4134012
$2s^2\ 2p4s$	$^3P^o$	0	-	4395728	5520070
$2s^2\ 2p4s$	$^3P^o$	1	-	4396731	5522133
$2s^2\ 2p4s$	$^3P^o$	2	-	4431652	5556429
$2s^2\ 2p4s$	$^1P^o$	1	-	4433840	5561725
$2s^2\ 2p5s$	$^3P^o$	0	-	4657441	-
$2s^2\ 2p5s$	$^3P^o$	1	-	4657861	-
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$2s^2\ 2p5s$	$^3P^o$	0	-	4657441	-
$2s^2\ 2p5s$	$^3P^o$	1	-	4657861	-
$2s^2\ 2p5s$	$^3P^o$	2	-	4693386	-
$2s^2\ 2p5s$	$^1P^o$	1	-	4694256	-

Atomic structure of the Ca XV ion

"Energy levels for the configuration $2s^2$ 2p 3p of Ca XV."

E(NIST) are from NIST database, E(CW) are the energy levels calculated by using the Cowan (CW) code, and E(EK) calculated by Ekman et al. using the MCDHF method. All energies are in cm^{-1}.

Conf.	Term	J	E(NIST)	E(CW)	E(EK)
$2s^2$ 2p3p	^3S	1	-	4476007	4257457
$2s^2$ 2p3p	^1P	1	-	4446957	4228086
$2s^2$ 2p3p	^3D	1	-	4424400	4205709
$2s^2$ 2p3p	^3D	2	-	4445944	4229376
$2s^2$ 2p3p	^3D	3	-	4472023	4255295
$2s^2$ 2p3p	^3P	0	-	4475994	4250224
$2s^2$ 2p3p	^3P	1	-	4494910	4270847
$2s^2$ 2p3p	^3P	2	-	4501838	4276163
$2s^2$ 2p3p	^1D	2	-	4528268	4314496
$2s^2$ 2p3p	^1S	0	-	4567681	4361378

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Conf.	Term	J	E(NIST)	E(CW)	E(EK)
$2s^2$ 2p4p	^{3}S	1	-	4491238	5618735
$2s^2$ 2p4p	^{1}P	1	-	4487896	5612050
$2s^2$ 2p4p	^{3}D	1	-	4450829	5572096
$2s^2$ 2p4p	^{3}D	2	-	4456178	5583680
$2s^2$ 2p4p	^{3}D	3	-	4488453	5613455
$2s^2$ 2p4p	^{3}P	0	-	4459660	5590557
$2s^2$ 2p4p	^{3}P	1	-	4455693	5582839
$2s^2$ 2p4p	^{3}P	2	-	4491171	5619232
$2s^2$ 2p4p	^{1}D	2	-	4496043	5631037
$2s^2$ 2p4p	^{1}S	0	-	4501924	-

Atomic structure of the Ca XV ion

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Conf.	Term	J	E(NIST)	E(CW)	E(EK)
$2s^2$ 2p3d	$^3F^o$	2	4363300	3951477	4363635
$2s^2$ 2p3d	$^3F^o$	3	4379400	3963833	4378814
$2s^2$ 2p3d	$^3F^o$	4	-	3988654	4401309
$2s^2$ 2p3d	$^1D^o$	2	-	3966033	4385007
$2s^2$ 2p3d	$^3D^o$	1	4399500	3975409	4402470
$2s^2$ 2p3d	$^3D^o$	2	4411500	3991878	4413002
$2s^2$ 2p3d	$^3D^o$	3	4426400	4000316	4425526
$2s^2$ 2p3d	$^3P^o$	2	4435400	4006954	4433389
$2s^2$ 2p3d	$^3P^o$	1	4434500	4008947	4435381
$2s^2$ 2p3d	$^3P^o$	0	-	4010358	4436968
$2s^2$ 2p3d	$^1F^o$	3	4475000	4032514	4474373
$2s^2$ 2p3d	$^1P^o$	1	4473400	4032524	4475119
				9.6%	0.03%

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Atomic structure of the Ca XV ion

2.Oscillator strengths and transition probabilities of the different transitions for Ca XV:

"Weighted oscillator strengths and transition probabilities for the transition ($2s^2 2p^2\ ^3P$ - $2s\ 2p^3\ ^3S^o$) of Ca XV ion."

$\log gf$ (CW), $\log gf$ (EK) and gA (CW) and gA (EK) are the wighted oscillator strengths and transition probabilities calculated by us and by Ekman et al. using the Cowan code and the MCDHF method respectively. g_i and g_k are respectively the statistical wights of the term ^3P -$^3S^o$.

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			log gf		gA	
λ (nm)	g_i	g_k	(CW)	(EK)	(CW)	(EK)
13.9	5	3	-0.317	-0.462	1.68E+11	1.11E+11
13.5	3	3	-0.599	-0.762	9.22E+10	5.82E+10
13.2	1	3	-1.076	-1.249	3.21E+10	2.00E+10
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			log gf		gA	
λ (nm)	g_i	g_k	(CW)	(EK)	(CW)	(EK)
17.46058	5	3	-1.34	-1.32	1.01E+10	9.54E+09
17.36467	5	5	-0.59	-0.61	5.75E+10	4.91E+10
16.95419	3	1	-1.25	-1.25	1.31E+10	1.20E+10
16.90512	3	3	-1.07	-1.12	1.98E+10	1.61E+10
16.8152	3	5	-1.68	-1.54	4.94E+09	6.15E+09
16.45036	1	3	-1.41	-1.37	9.59E+09	9.66E+09
				3.6%		12.6%

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20.25	5	5	-1.790	-2.105	2.64E+09	1.11E+09
20.22	5	3	-2.992	-3.365	1.66E+08	6.15E+07
20.05	5	7	-0.500	-0.699	5.24E+10	2.88E+10
19.51	3	5	-0.644	-0.815	3.98E+10	2.34E+10
19.48	3	3	-1.399	-1.616	7.02E+09	3.72E+09
18.88	1	3	-0.956	-1.126	2.07E+10	1.24E+10
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