Experimental Radiative Near-infrared Atomic Data for Kilonova Spectroscopy

Henrik Hartman
Malmö university, Sweden

The Radiative Transfer and Atomic Physics of Kilonovae,
Stockholm September 4-7, 2023

Atomic Spectroscopy Laboratory - University of Valladolid (Spain)

Dr Teruca Belmonte

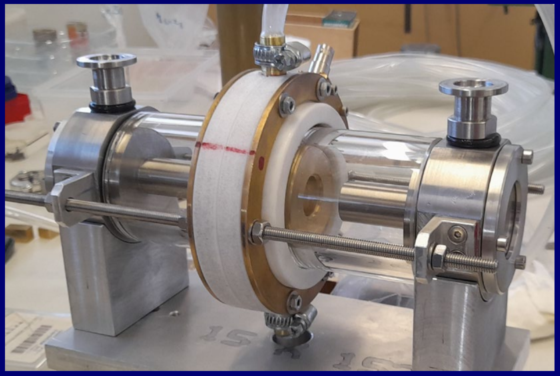
Pratyush Sen Sarma

Prof Santiago Mar

We are focusing on the **measurement** of **TRANSITION PROBABILITIES** (oscillator strengths) of rare earth elements, in particular **Nd III** (Pratyush´s PhD) (collaboration with Imperial College London)

OUR CAPABILITIES

- Neutral, singly and doubly ionised atomic spectra (hollow-cathode lamp)
- Spectral range: UV-visible (200 – 800 nm)
- 1.5 m diffraction grating monochromator (Czerny-Turner, 2400 lines/mm)
- Resolving power: 150 000 (at 450 nm)
- Setting-up a Fabry-Pérot interferometer



Collaborators

Laboratory spectroscopy (Malmö and Lund universities):
Hampus Nilsson, Madeleine Burheim, Asli Pehlivan Rhodin (until 2018), Lars Engström

Calculations (GRASP2k and ATSP2k):
Per Jönsson, Jörgen Ekman, Yanting Li (Malmö University)
Jon Grumer, Sema Caliskan (Uppsala University)

Collaborations:
LUMCAS: Wenxian Li, Rickard du Rietz, Stefan Gustafsson, Nils Ryde, Brian Thorsbro, Si Ran, Tomas Brage
CompAS; Imperial College London; Atomic Spectroscopy group at NIST
Dr Belmonte at Valladolid university, Spain

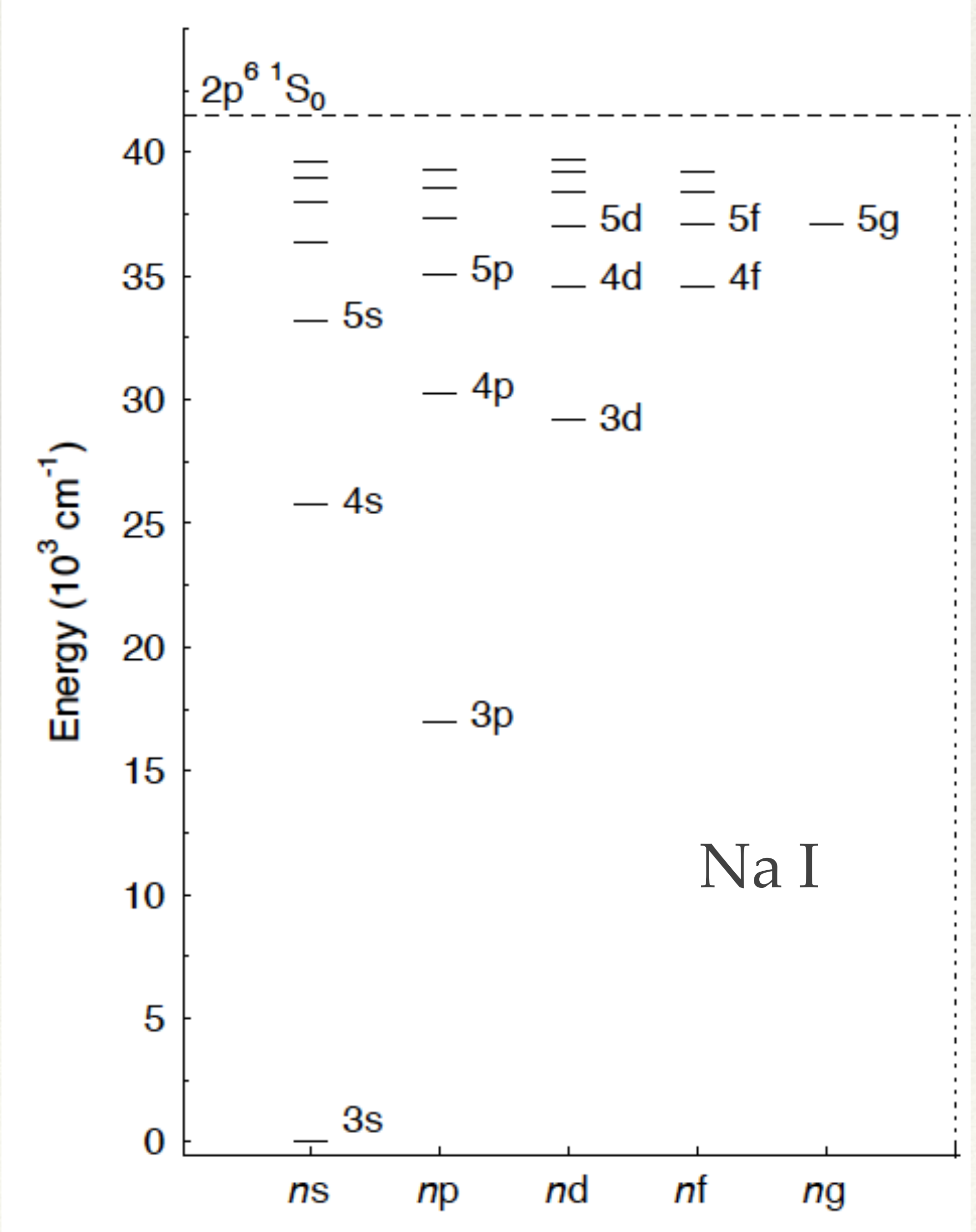
VETENSKAPSRÅDET
THE SWEDISH RESEARCH COUNCIL

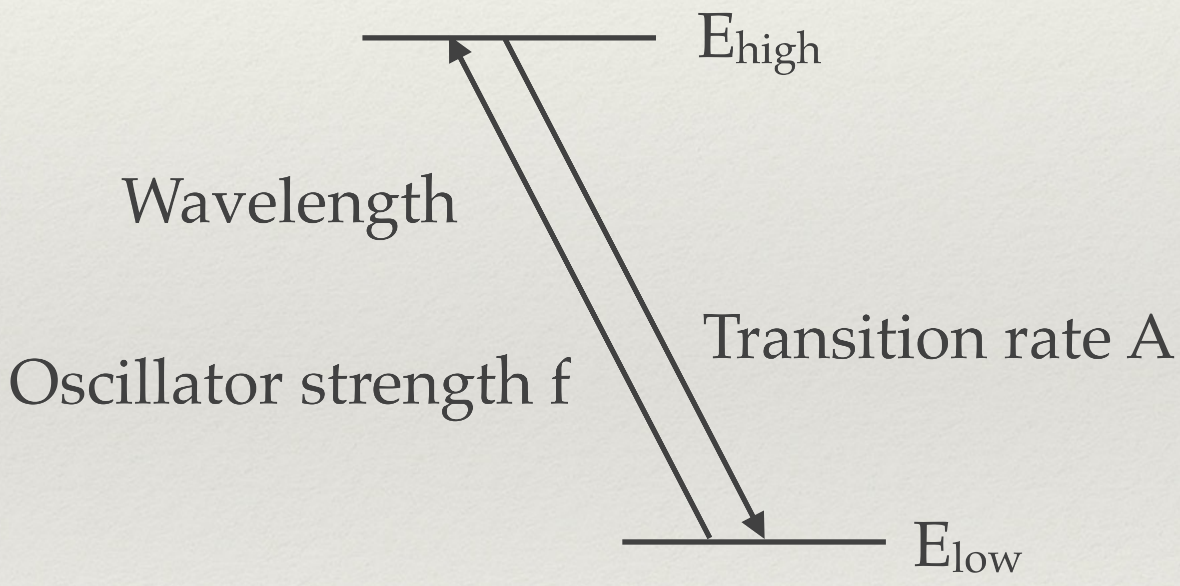
Gyllenstiernska
Krapperupsstiftelsen

The Crafoord Foundation
ESTABLISHED BY HOLGER CRAFOORD IN 1980

The Basics

The so-called allowed atomic transitions are between odd and even parity states, and the wavelength is determined by the energy difference.





E_{high}

Wavelength

Transition rate A

Oscillator strength f

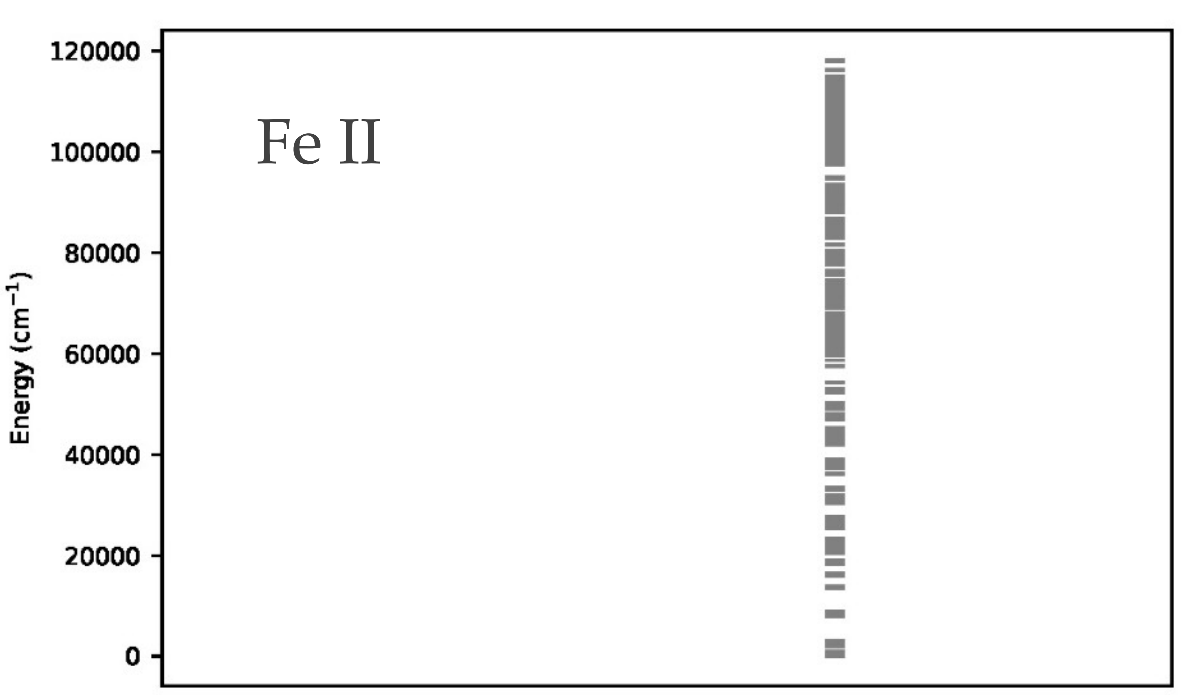
E_{low}

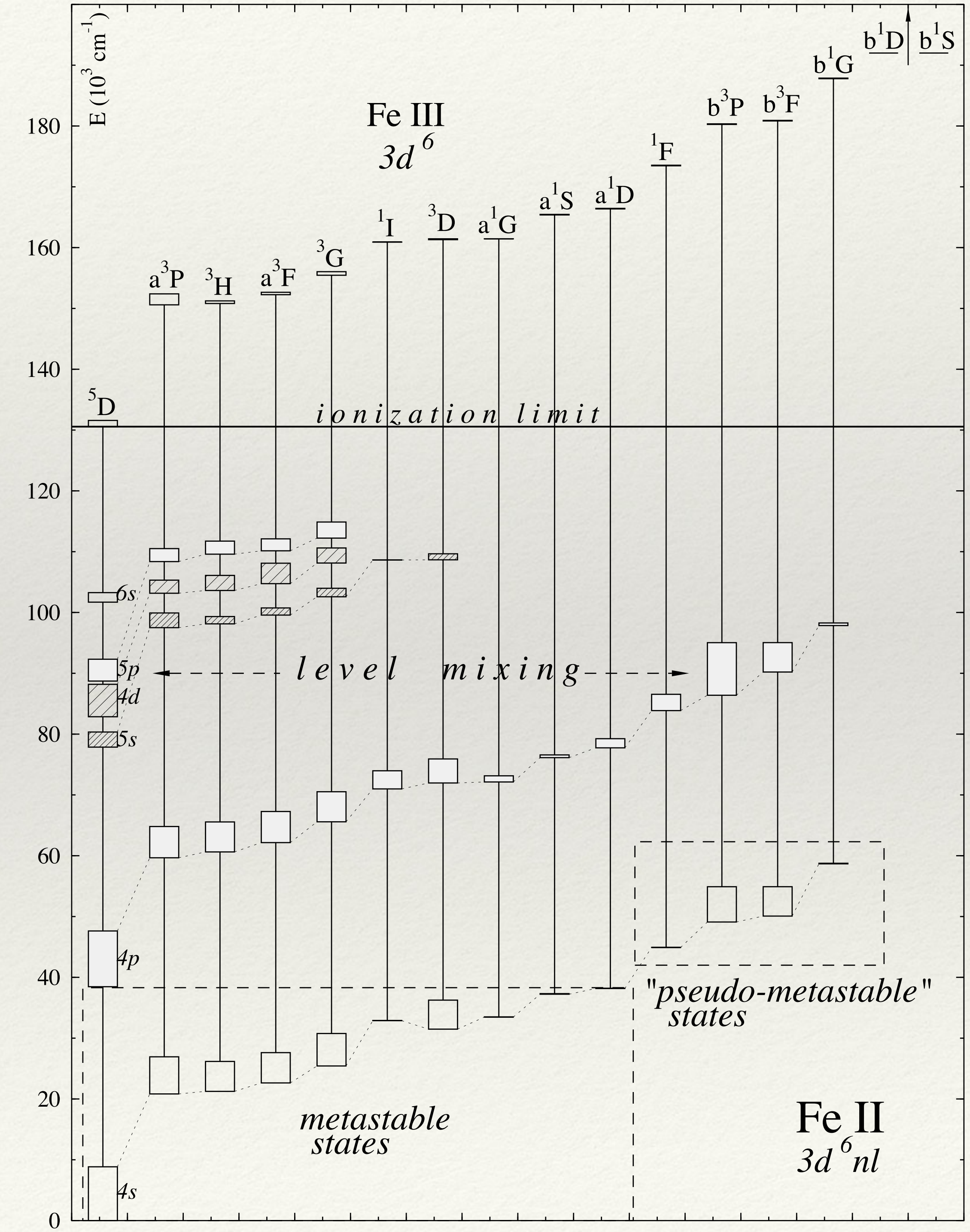
Close levels - infrared transitions

Well separated levels - optical or ultraviolet transitions

Energy level diagram

The energy level diagram can include the physics to understand the spectrum and the spectral lines.





Different needs of radiative data

The need of atomic data in terms of parameters and quality is dependent on the application:

Stellar abundances - individual lines: wavelength, accurate oscillator strengths, line structure (hyperfine structure)

Exoplanet atmosphere detection - wavelength, approximate line strength

Kilonova light curves - broad opacity, completeness

Kilonova spectra - rather accurate wavelength, rather accurate strengths

The near-infrared region (1-5 microns) is particularly empty of atomic data.
This was the case for the ultraviolet region before the *Hubble Space Telescope* launch in 1990s.

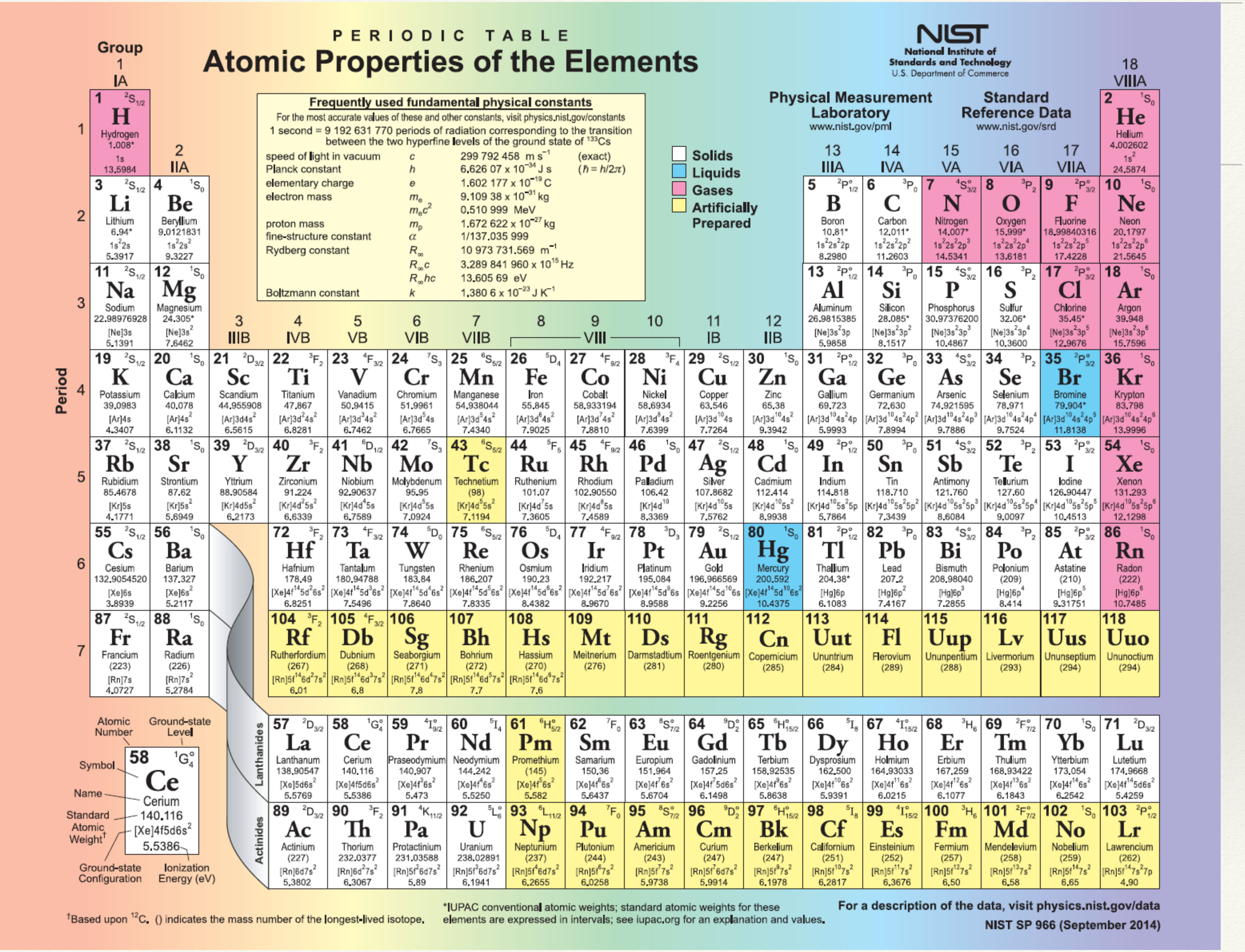
near-IR atomic transitions

Near-IR transitions (1-5 microns) from an atomic physics point of view, appear differently in different ions and depend on the atomic structure: (remember, near-IR = levels close in energy):

:: High-excitation transitions; Rydberg states

:: Lower excitation transitions in some complex atomic spectra

:: Resonance lines in heavier elements, e.g. third spectra of rare-earth elements



P E R I O D I C   T A B L E

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1 second = 9 192 631 770 periods of radiation corresponding to the transition between the two hyperfine levels of the ground state of ^{133}Cs

speed of light in vacuum	c	299 792 458 m s^{-1}	(exact)
Planck constant	h	6.626 07 x 10^{-34} J s	($\hbar = h/2\pi$)
elementary charge	e	1.602 177 x 10^{-19} C	
electron mass	m_e	9.109 38 x 10^{-31} kg	
	$m_e c^2$	0.510 999 MeV	
proton mass	m_p	1.672 622 x 10^{-27} kg	
fine-structure constant	α	1/137.035 999	
Rydberg constant	R_∞	10 973 731.569 m^{-1}	
	$R_\infty c$	3.289 841 960 x 10^{15} Hz	
	$R_\infty hc$	13.605 69 eV	
Boltzmann constant	k	1.380 6 x 10^{-23} J K^{-1}	

☐ Solids
🟦 Liquids
🟥 Gases
🟨 Artificially Prepared

Period	Group 1 IA	2 IIA	3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8 VIII	9	10	11 IB	12 IIB	13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	18 VIIIA
1	1 $^{2}S_{1/2}$ **H** Hydrogen 1.008* $1s$ 13.5984																	2 $^{1}S_{0}$ **He** Helium 4.002602 $1s^{2}$ 24.5874
2	3 $^{2}S_{1/2}$ **Li** Lithium 6.94* $1s^{2}2s$ 5.3917	4 $^{1}S_{0}$ **Be** Beryllium 9.0121831 $1s^{2}2s^{2}$ 9.3227											5 $^{2}P^{\circ}_{1/2}$ **B** Boron 10.81* $1s^{2}2s^{2}2p$ 8.2980	6 $^{3}P_{0}$ **C** Carbon 12.011* $1s^{2}2s^{2}2p^{2}$ 11.2603	7 $^{4}S^{\circ}_{3/2}$ **N** Nitrogen 14.007* $1s^{2}2s^{2}2p^{3}$ 14.5341	8 $^{3}P_{2}$ **O** Oxygen 15.999* $1s^{2}2s^{2}2p^{4}$ 13.6181	9 $^{2}P^{\circ}_{3/2}$ **F** Fluorine 18.99840316 $1s^{2}2s^{2}2p^{5}$ 17.4228	10 $^{1}S_{0}$ **Ne** Neon 20.1797 $1s^{2}2s^{2}2p^{6}$ 21.5645
3	11 $^{2}S_{1/2}$ **Na** Sodium 22.98976928 $[Ne]3s$ 5.1391	12 $^{1}S_{0}$ **Mg** Magnesium 24.305* $[Ne]3s^{2}$ 7.6462											13 $^{2}P^{\circ}_{1/2}$ **Al** Aluminum 26.9815385 $[Ne]3s^{2}3p$ 5.9858	14 $^{3}P_{0}$ **Si** Silicon 28.085* $[Ne]3s^{2}3p^{2}$ 8.1517	15 $^{4}S^{\circ}_{3/2}$ **P** Phosphorus 30.97376200 $[Ne]3s^{2}3p^{3}$ 10.4867	16 $^{3}P_{2}$ **S** Sulfur 32.06* $[Ne]3s^{2}3p^{4}$ 10.3600	17 $^{2}P^{\circ}_{3/2}$ **Cl** Chlorine 35.45* $[Ne]3s^{2}3p^{5}$ 12.9676	18 $^{1}S_{0}$ **Ar** Argon 39.948 $[Ne]3s^{2}3p^{6}$ 15.7596
4	19 $^{2}S_{1/2}$ **K** Potassium 39.0983 $[Ar]4s$ 4.3407	20 $^{1}S_{0}$ **Ca** Calcium 40.078 $[Ar]4s^{2}$ 6.1132	21 $^{2}D_{3/2}$ **Sc** Scandium 44.955908 $[Ar]3d4s^{2}$ 6.5615	22 $^{3}F_{2}$ **Ti** Titanium 47.867 $[Ar]3d^{2}4s^{2}$ 6.8281	23 $^{4}F_{3/2}$ **V** Vanadium 50.9415 $[Ar]3d^{3}4s^{2}$ 6.7462	24 $^{7}S_{3}$ **Cr** Chromium 51.9961 $[Ar]3d^{5}4s$ 6.7665	25 $^{6}S_{5/2}$ **Mn** Manganese 54.938044 $[Ar]3d^{5}4s^{2}$ 7.4340	26 $^{5}D_{4}$ **Fe** Iron 55.845 $[Ar]3d^{6}4s^{2}$ 7.9025	27 $^{4}F_{9/2}$ **Co** Cobalt 58.933194 $[Ar]3d^{7}4s^{2}$ 7.8810	28 $^{3}F_{4}$ **Ni** Nickel 58.6934 $[Ar]3d^{8}4s^{2}$ 7.6399	29 $^{2}S_{1/2}$ **Cu** Copper 63.546 $[Ar]3d^{10}4s$ 7.7264	30 $^{1}S_{0}$ **Zn** Zinc 65.38 $[Ar]3d^{10}4s^{2}$ 9.3942	31 $^{2}P^{\circ}_{1/2}$ **Ga** Gallium 69.723 $[Ar]3d^{10}4s^{2}4p$ 5.9993	32 $^{3}P_{0}$ **Ge** Germanium 72.630 $[Ar]3d^{10}4s^{2}4p^{2}$ 7.8994	33 $^{4}S^{\circ}_{3/2}$ **As** Arsenic 74.921595 $[Ar]3d^{10}4s^{2}4p^{3}$ 9.7886	34 $^{3}P_{2}$ **Se** Selenium 78.971 $[Ar]3d^{10}4s^{2}4p^{4}$ 9.7524	35 $^{2}P^{\circ}_{3/2}$ **Br** Bromine 79.904* $[Ar]3d^{10}4s^{2}4p^{5}$ 11.8138	36 $^{1}S_{0}$ **Kr** Krypton 83.798 $[Ar]3d^{10}4s^{2}4p^{6}$ 13.9996
5	37 $^{2}S_{1/2}$ **Rb** Rubidium 85.4678 $[Kr]5s$ 4.1771	38 $^{1}S_{0}$ **Sr** Strontium 87.62 $[Kr]5s^{2}$ 5.6949	39 $^{2}D_{3/2}$ **Y** Yttrium 88.90584 $[Kr]4d5s^{2}$ 6.2173	40 $^{3}F_{2}$ **Zr** Zirconium 91.224 $[Kr]4d^{2}5s^{2}$ 6.6339	41 $^{6}D_{1/2}$ **Nb** Niobium 92.90637 $[Kr]4d^{4}5s$ 6.7589	42 $^{7}S_{3}$ **Mo** Molybdenum 95.95 $[Kr]4d^{5}5s$ 7.0924	43 $^{6}S_{5/2}$ **Tc** Technetium (98) $[Kr]4d^{5}5s^{2}$ 7.1194	44 $^{5}F_{5}$ **Ru** Ruthenium 101.07 $[Kr]4d^{7}5s$ 7.3605	45 $^{4}F_{9/2}$ **Rh** Rhodium 102.90550 $[Kr]4d^{8}5s$ 7.4589	46 $^{1}S_{0}$ **Pd** Palladium 106.42 $[Kr]4d^{10}$ 8.3369	47 $^{2}S_{1/2}$ **Ag** Silver 107.8682 $[Kr]4d^{10}5s$ 7.5762	48 $^{1}S_{0}$ **Cd** Cadmium 112.414 $[Kr]4d^{10}5s^{2}$ 8.9938	49 $^{2}P^{\circ}_{1/2}$ **In** Indium 114.818 $[Kr]4d^{10}5s^{2}5p$ 5.7864	50 $^{3}P_{0}$ **Sn** Tin 118.710 $[Kr]4d^{10}5s^{2}5p^{2}$ 7.3439	51 $^{4}S^{\circ}_{3/2}$ **Sb** Antimony 121.760 $[Kr]4d^{10}5s^{2}5p^{3}$ 8.6084	52 $^{3}P_{2}$ **Te** Tellurium 127.60 $[Kr]4d^{10}5s^{2}5p^{4}$ 9.0097	53 $^{2}P^{\circ}_{3/2}$ **I** Iodine 126.90447 $[Kr]4d^{10}5s^{2}5p^{5}$ 10.4513	54 $^{1}S_{0}$ **Xe** Xenon 131.293 $[Kr]4d^{10}5s^{2}5p^{6}$ 12.1298
6	55 $^{2}S_{1/2}$ **Cs** Cesium 132.9054520 $[Xe]6s$ 3.8939	56 $^{1}S_{0}$ **Ba** Barium 137.327 $[Xe]6s^{2}$ 5.2117		72 $^{3}F_{2}$ **Hf** Hafnium 178.49 $[Xe]4f^{14}5d^{2}6s^{2}$ 6.8251	73 $^{4}F_{3/2}$ **Ta** Tantalum 180.94788 $[Xe]4f^{14}5d^{3}6s^{2}$ 7.5496	74 $^{5}D_{0}$ **W** Tungsten 183.84 $[Xe]4f^{14}5d^{4}6s^{2}$ 7.8640	75 $^{6}S_{5/2}$ **Re** Rhenium 186.207 $[Xe]4f^{14}5d^{5}6s^{2}$ 7.8335	76 $^{5}D_{4}$ **Os** Osmium 190.23 $[Xe]4f^{14}5d^{6}6s^{2}$ 8.4382	77 $^{4}F_{9/2}$ **Ir** Iridium 192.217 $[Xe]4f^{14}5d^{7}6s^{2}$ 8.9670	78 $^{3}D_{3}$ **Pt** Platinum 195.084 $[Xe]4f^{14}5d^{9}6s$ 8.9588	79 $^{2}S_{1/2}$ **Au** Gold 196.966569 $[Xe]4f^{14}5d^{10}6s$ 9.2256	80 $^{1}S_{0}$ **Hg** Mercury 200.592 $[Xe]4f^{14}5d^{10}6s^{2}$ 10.4375	81 $^{2}P^{\circ}_{1/2}$ **Tl** Thallium 204.38* $[Hg]6p$ 6.1083	82 $^{3}P_{0}$ **Pb** Lead 207.2 $[Hg]6p^{2}$ 7.4167	83 $^{4}S^{\circ}_{3/2}$ **Bi** Bismuth 208.98040 $[Hg]6p^{3}$ 7.2855	84 $^{3}P_{2}$ **Po** Polonium (209) $[Hg]6p^{4}$ 8.414	85 $^{2}P^{\circ}_{3/2}$ **At** Astatine (210) $[Hg]6p^{5}$ 9.31751	86 $^{1}S_{0}$ **Rn** Radon (222) $[Hg]6p^{6}$ 10.7485
7	87 $^{2}S_{1/2}$ **Fr** Francium (223) $[Rn]7s$ 4.0727	88 $^{1}S_{0}$ **Ra** Radium (226) $[Rn]7s^{2}$ 5.2784		104 $^{3}F_{2}$ **Rf** Rutherfordium (267) $[Rn]5f^{14}6d^{2}7s^{2}$ 6.01	105 $^{4}F_{3/2}$ **Db** Dubnium (268) $[Rn]5f^{14}6d^{3}7s^{2}$ 6.8	106 **Sg** Seaborgium (271) $[Rn]5f^{14}6d^{4}7s^{2}$ 7.8	107 **Bh** Bohrium (272) $[Rn]5f^{14}6d^{5}7s^{2}$ 7.7	108 **Hs** Hassium (270) $[Rn]5f^{14}6d^{6}7s^{2}$ 7.6	109 **Mt** Meitnerium (276)	110 **Ds** Darmstadtium (281)	111 **Rg** Roentgenium (280)	112 **Cn** Copernicium (285)	113 **Uut** Ununtrium (284)	114 **Fl** Flerovium (289)	115 **Uup** Ununpentium (288)	116 **Lv** Livermorium (293)	117 **Uus** Ununseptium (294)	118 **Uuo** Ununoctium (294)

Lanthanides	57 $^{2}D_{3/2}$ **La** Lanthanum 138.90547 $[Xe]5d6s^{2}$ 5.5769	58 $^{1}G^{\circ}_{4}$ **Ce** Cerium 140.116 $[Xe]4f5d6s^{2}$ 5.5386	59 $^{4}I^{\circ}_{9/2}$ **Pr** Praseodymium 140.907 $[Xe]4f^{3}6s^{2}$ 5.473	60 $^{5}I_{4}$ **Nd** Neodymium 144.242 $[Xe]4f^{4}6s^{2}$ 5.5250	61 $^{6}H^{\circ}_{5/2}$ **Pm** Promethium (145) $[Xe]4f^{5}6s^{2}$ 5.582	62 $^{7}F_{0}$ **Sm** Samarium 150.36 $[Xe]4f^{6}6s^{2}$ 5.6437	63 $^{8}S^{\circ}_{7/2}$ **Eu** Europium 151.964 $[Xe]4f^{7}6s^{2}$ 5.6704	64 $^{9}D^{\circ}_{2}$ **Gd** Gadolinium 157.25 $[Xe]4f^{7}5d6s^{2}$ 6.1498	65 $^{6}H^{\circ}_{15/2}$ **Tb** Terbium 158.92535 $[Xe]4f^{9}6s^{2}$ 5.8638	66 $^{5}I_{8}$ **Dy** Dysprosium 162.500 $[Xe]4f^{10}6s^{2}$ 5.9391	67 $^{4}I^{\circ}_{15/2}$ **Ho** Holmium 164.93033 $[Xe]4f^{11}6s^{2}$ 6.0215	68 $^{3}H_{6}$ **Er** Erbium 167.259 $[Xe]4f^{12}6s^{2}$ 6.1077	69 $^{2}F^{\circ}_{7/2}$ **Tm** Thulium 168.93422 $[Xe]4f^{13}6s^{2}$ 6.1843	70 $^{1}S_{0}$ **Yb** Ytterbium 173.054 $[Xe]4f^{14}6s^{2}$ 6.2542	71 $^{2}D_{3/2}$ **Lu** Lutetium 174.9668 $[Xe]4f^{14}5d6s^{2}$ 5.4259
Actinides	89 $^{2}D_{3/2}$ **Ac** Actinium (227) $[Rn]6d7s^{2}$ 5.3802	90 $^{3}F_{2}$ **Th** Thorium 232.0377 $[Rn]6d^{2}7s^{2}$ 6.3067	91 $^{4}K_{11/2}$ **Pa** Protactinium 231.03588 $[Rn]5f^{2}6d7s^{2}$ 5.89	92 $^{5}L^{\circ}_{6}$ **U** Uranium 238.02891 $[Rn]5f^{3}6d7s^{2}$ 6.1941	93 $^{6}L_{11/2}$ **Np** Neptunium (237) $[Rn]5f^{4}6d7s^{2}$ 6.2655	94 $^{7}F_{0}$ **Pu** Plutonium (244) $[Rn]5f^{6}7s^{2}$ 6.0258	95 $^{8}S^{\circ}_{7/2}$ **Am** Americium (243) $[Rn]5f^{7}7s^{2}$ 5.9738	96 $^{9}D^{\circ}_{2}$ **Cm** Curium (247) $[Rn]5f^{7}6d7s^{2}$ 5.9914	97 $^{6}H^{\circ}_{15/2}$ **Bk** Berkelium (247) $[Rn]5f^{9}7s^{2}$ 6.1978	98 $^{5}I_{8}$ **Cf** Californium (251) $[Rn]5f^{10}7s^{2}$ 6.2817	99 $^{4}I^{\circ}_{15/2}$ **Es** Einsteinium (252) $[Rn]5f^{11}7s^{2}$ 6.3676	100 $^{3}H_{6}$ **Fm** Fermium (257) $[Rn]5f^{12}7s^{2}$ 6.50	101 $^{2}F^{\circ}_{7/2}$ **Md** Mendelevium (258) $[Rn]5f^{13}7s^{2}$ 6.58	102 $^{1}S_{0}$ **No** Nobelium (259) $[Rn]5f^{14}7s^{2}$ 6.65	103 $^{2}P^{\circ}_{1/2}$ **Lr** Lawrencium (262) $[Rn]5f^{14}7s^{2}7p$ 4.90

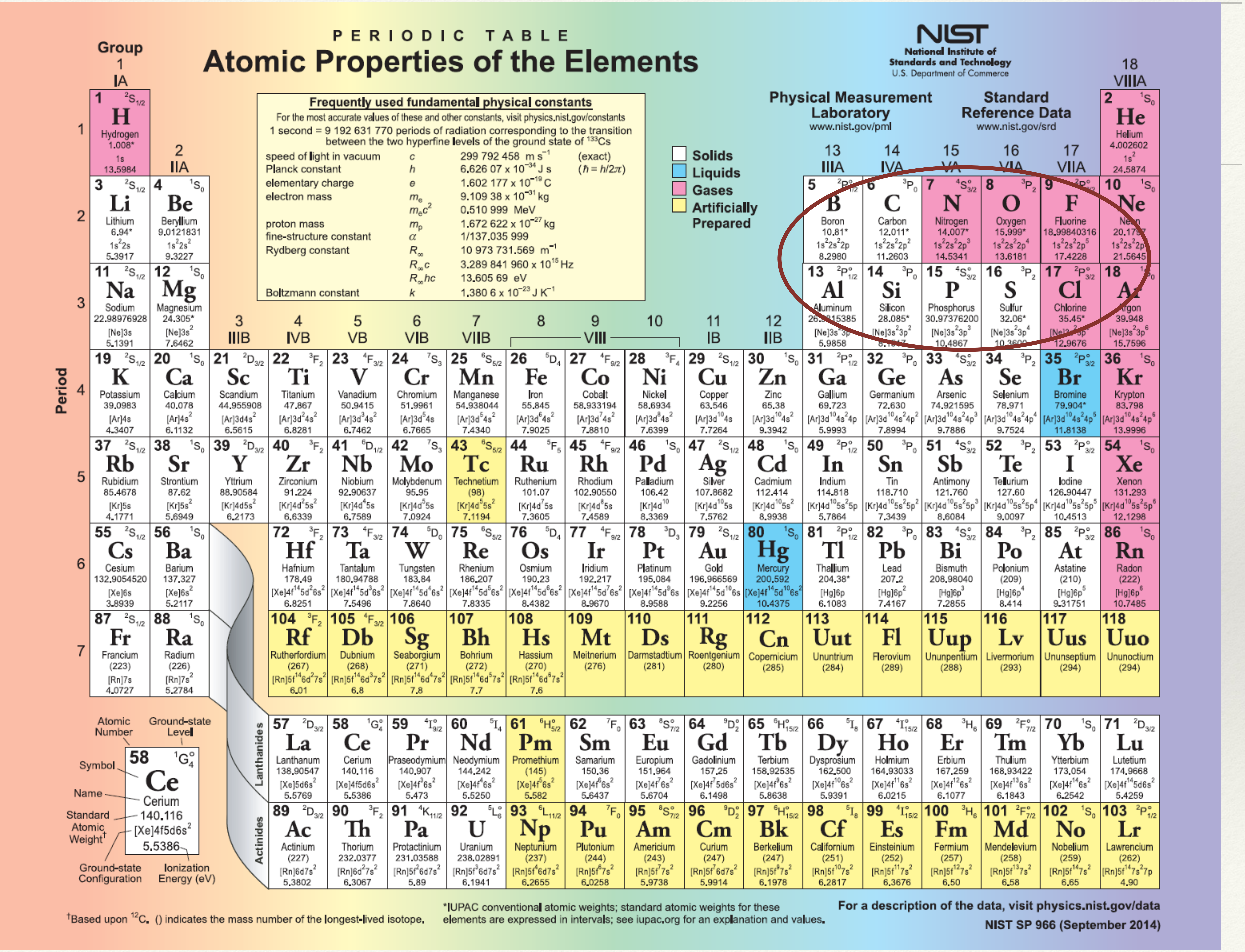
Atomic Number — 58
Ground-state Level — $^{1}G^{\circ}_{4}$
Symbol — **Ce**
Name — Cerium
Standard Atomic Weight† — 140.116
Ground-state Configuration — $[Xe]4f5d6s^{2}$
Ionization Energy (eV) — 5.5386

†Based upon ^{12}C. () indicates the mass number of the longest-lived isotope.

*IUPAC conventional atomic weights; standard atomic weights for these elements are expressed in intervals; see iupac.org for an explanation and values.

For a description of the data, visit physics.nist.gov/data

NIST SP 966 (September 2014)



PERIODIC TABLE

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3	11 $^2S_{1/2}$ **Na** Sodium 22.98976928 $[Ne]3s$ 5.1391	12 $^1S_0$ **Mg** Magnesium 24.305* $[Ne]3s^2$ 7.6462											13 $^2P^\circ_{1/2}$ **Al** Aluminum 26.9815385 $[Ne]3s^23p$ 5.9858	14 $^3P_0$ **Si** Silicon 28.085* $[Ne]3s^23p^2$ 8.1517	15 $^4S^\circ_{3/2}$ **P** Phosphorus 30.97376200 $[Ne]3s^23p^3$ 10.4867	16 $^3P_2$ **S** Sulfur 32.06* $[Ne]3s^23p^4$ 10.3600	17 $^2P^\circ_{3/2}$ **Cl** Chlorine 35.45* $[Ne]3s^23p^5$ 12.9676	18 $^1S_0$ **Ar** Argon 39.948 $[Ne]3s^23p^6$ 15.7596
4	19 $^2S_{1/2}$ **K** Potassium 39.0983 $[Ar]4s$ 4.3407	20 $^1S_0$ **Ca** Calcium 40.078 $[Ar]4s^2$ 6.1132	21 $^2D_{3/2}$ **Sc** Scandium 44.955908 $[Ar]3d4s^2$ 6.5615	22 $^3F_2$ **Ti** Titanium 47.867 $[Ar]3d^24s^2$ 6.8281	23 $^4F_{3/2}$ **V** Vanadium 50.9415 $[Ar]3d^34s^2$ 6.7462	24 $^7S_3$ **Cr** Chromium 51.9961 $[Ar]3d^54s$ 6.7665	25 $^6S_{5/2}$ **Mn** Manganese 54.938044 $[Ar]3d^54s^2$ 7.4340	26 $^5D_4$ **Fe** Iron 55.845 $[Ar]3d^64s^2$ 7.9025	27 $^4F_{9/2}$ **Co** Cobalt 58.933194 $[Ar]3d^74s^2$ 7.8810	28 $^3F_4$ **Ni** Nickel 58.6934 $[Ar]3d^84s^2$ 7.6399	29 $^2S_{1/2}$ **Cu** Copper 63.546 $[Ar]3d^{10}4s$ 7.7264	30 $^1S_0$ **Zn** Zinc 65.38 $[Ar]3d^{10}4s^2$ 9.3942	31 $^2P^\circ_{1/2}$ **Ga** Gallium 69.723 $[Ar]3d^{10}4s^24p$ 5.9993	32 $^3P_0$ **Ge** Germanium 72.630 $[Ar]3d^{10}4s^24p^2$ 7.8994	33 $^4S^\circ_{3/2}$ **As** Arsenic 74.921595 $[Ar]3d^{10}4s^24p^3$ 9.7886	34 $^3P_2$ **Se** Selenium 78.971 $[Ar]3d^{10}4s^24p^4$ 9.7524	35 $^2P^\circ_{3/2}$ **Br** Bromine 79.904* $[Ar]3d^{10}4s^24p^5$ 11.8138	36 $^1S_0$ **Kr** Krypton 83.798 $[Ar]3d^{10}4s^24p^6$ 13.9996
5	37 $^2S_{1/2}$ **Rb** Rubidium 85.4678 $[Kr]5s$ 4.1771	38 $^1S_0$ **Sr** Strontium 87.62 $[Kr]5s^2$ 5.6949	39 $^2D_{3/2}$ **Y** Yttrium 88.90584 $[Kr]4d5s^2$ 6.2173	40 $^3F_2$ **Zr** Zirconium 91.224 $[Kr]4d^25s^2$ 6.6339	41 $^6D_{1/2}$ **Nb** Niobium 92.90637 $[Kr]4d^45s$ 6.7589	42 $^7S_3$ **Mo** Molybdenum 95.95 $[Kr]4d^55s$ 7.0924	43 $^6S_{5/2}$ **Tc** Technetium (98) $[Kr]4d^55s^2$ 7.1194	44 $^5F_5$ **Ru** Ruthenium 101.07 $[Kr]4d^75s$ 7.3605	45 $^4F_{9/2}$ **Rh** Rhodium 102.90550 $[Kr]4d^85s$ 7.4589	46 $^1S_0$ **Pd** Palladium 106.42 $[Kr]4d^{10}$ 8.3369	47 $^2S_{1/2}$ **Ag** Silver 107.8682 $[Kr]4d^{10}5s$ 7.5762	48 $^1S_0$ **Cd** Cadmium 112.414 $[Kr]4d^{10}5s^2$ 8.9938	49 $^2P^\circ_{1/2}$ **In** Indium 114.818 $[Kr]4d^{10}5s^25p$ 5.7864	50 $^3P_0$ **Sn** Tin 118.710 $[Kr]4d^{10}5s^25p^2$ 7.3439	51 $^4S^\circ_{3/2}$ **Sb** Antimony 121.760 $[Kr]4d^{10}5s^25p^3$ 8.6084	52 $^3P_2$ **Te** Tellurium 127.60 $[Kr]4d^{10}5s^25p^4$ 9.0097	53 $^2P^\circ_{3/2}$ **I** Iodine 126.90447 $[Kr]4d^{10}5s^25p^5$ 10.4513	54 $^1S_0$ **Xe** Xenon 131.293 $[Kr]4d^{10}5s^25p^6$ 12.1298
6	55 $^2S_{1/2}$ **Cs** Cesium 132.9054520 $[Xe]6s$ 3.8939	56 $^1S_0$ **Ba** Barium 137.327 $[Xe]6s^2$ 5.2117		72 $^3F_2$ **Hf** Hafnium 178.49 $[Xe]4f^{14}5d^26s^2$ 6.8251	73 $^4F_{3/2}$ **Ta** Tantalum 180.94788 $[Xe]4f^{14}5d^36s^2$ 7.5496	74 $^5D_0$ **W** Tungsten 183.84 $[Xe]4f^{14}5d^46s^2$ 7.8640	75 $^6S_{5/2}$ **Re** Rhenium 186.207 $[Xe]4f^{14}5d^56s^2$ 7.8335	76 $^5D_4$ **Os** Osmium 190.23 $[Xe]4f^{14}5d^66s^2$ 8.4382	77 $^4F_{9/2}$ **Ir** Iridium 192.217 $[Xe]4f^{14}5d^76s^2$ 8.9670	78 $^3D_3$ **Pt** Platinum 195.084 $[Xe]4f^{14}5d^96s$ 8.9588	79 $^2S_{1/2}$ **Au** Gold 196.966569 $[Xe]4f^{14}5d^{10}6s$ 9.2256	80 $^1S_0$ **Hg** Mercury 200.592 $[Xe]4f^{14}5d^{10}6s^2$ 10.4375	81 $^2P^\circ_{1/2}$ **Tl** Thallium 204.38* $[Hg]6p$ 6.1083	82 $^3P_0$ **Pb** Lead 207.2 $[Hg]6p^2$ 7.4167	83 $^4S^\circ_{3/2}$ **Bi** Bismuth 208.98040 $[Hg]6p^3$ 7.2855	84 $^3P_2$ **Po** Polonium (209) $[Hg]6p^4$ 8.414	85 $^2P^\circ_{3/2}$ **At** Astatine (210) $[Hg]6p^5$ 9.31751	86 $^1S_0$ **Rn** Radon (222) $[Hg]6p^6$ 10.7485
7	87 $^2S_{1/2}$ **Fr** Francium (223) $[Rn]7s$ 4.0727	88 $^1S_0$ **Ra** Radium (226) $[Rn]7s^2$ 5.2784		104 $^3F_2$ **Rf** Rutherfordium (267) $[Rn]5f^{14}6d^27s^2$ 6.01	105 $^4F_{3/2}$ **Db** Dubnium (268) $[Rn]5f^{14}6d^37s^2$ 6.8	106 **Sg** Seaborgium (271) $[Rn]5f^{14}6d^47s^2$ 7.8	107 **Bh** Bohrium (272) $[Rn]5f^{14}6d^57s^2$ 7.7	108 **Hs** Hassium (270) $[Rn]5f^{14}6d^67s^2$ 7.6	109 **Mt** Meitnerium (276)	110 **Ds** Darmstadtium (281)	111 **Rg** Roentgenium (280)	112 **Cn** Copernicium (285)	113 **Uut** Ununtrium (284)	114 **Fl** Flerovium (289)	115 **Uup** Ununpentium (288)	116 **Lv** Livermorium (293)	117 **Uus** Ununseptium (294)	118 **Uuo** Ununoctium (294)

Lanthanides	57 $^2D_{3/2}$ **La** Lanthanum 138.90547 $[Xe]5d6s^2$ 5.5769	58 $^1G^\circ_4$ **Ce** Cerium 140.116 $[Xe]4f5d6s^2$ 5.5386	59 $^4I^\circ_{9/2}$ **Pr** Praseodymium 140.907 $[Xe]4f^36s^2$ 5.473	60 $^5I_4$ **Nd** Neodymium 144.242 $[Xe]4f^46s^2$ 5.5250	61 $^6H^\circ_{5/2}$ **Pm** Promethium (145) $[Xe]4f^56s^2$ 5.582	62 $^7F_0$ **Sm** Samarium 150.36 $[Xe]4f^66s^2$ 5.6437	63 $^8S^\circ_{7/2}$ **Eu** Europium 151.964 $[Xe]4f^76s^2$ 5.6704	64 $^9D^\circ_2$ **Gd** Gadolinium 157.25 $[Xe]4f^75d6s^2$ 6.1498	65 $^6H^\circ_{15/2}$ **Tb** Terbium 158.92535 $[Xe]4f^96s^2$ 5.8638	66 $^5I_8$ **Dy** Dysprosium 162.500 $[Xe]4f^{10}6s^2$ 5.9391	67 $^4I^\circ_{15/2}$ **Ho** Holmium 164.93033 $[Xe]4f^{11}6s^2$ 6.0215	68 $^3H_6$ **Er** Erbium 167.259 $[Xe]4f^{12}6s^2$ 6.1077	69 $^2F^\circ_{7/2}$ **Tm** Thulium 168.93422 $[Xe]4f^{13}6s^2$ 6.1843	70 $^1S_0$ **Yb** Ytterbium 173.054 $[Xe]4f^{14}6s^2$ 6.2542	71 $^2D_{3/2}$ **Lu** Lutetium 174.9668 $[Xe]4f^{14}5d6s^2$ 5.4259
Actinides	89 $^2D_{3/2}$ **Ac** Actinium (227) $[Rn]6d7s^2$ 5.3802	90 $^3F_2$ **Th** Thorium 232.0377 $[Rn]6d^27s^2$ 6.3067	91 $^4K_{11/2}$ **Pa** Protactinium 231.03588 $[Rn]5f^26d7s^2$ 5.89	92 $^5L^\circ_6$ **U** Uranium 238.02891 $[Rn]5f^36d7s^2$ 6.1941	93 $^6L_{11/2}$ **Np** Neptunium (237) $[Rn]5f^46d7s^2$ 6.2655	94 $^7F_0$ **Pu** Plutonium (244) $[Rn]5f^67s^2$ 6.0258	95 $^8S^\circ_{7/2}$ **Am** Americium (243) $[Rn]5f^77s^2$ 5.9738	96 $^9D^\circ_2$ **Cm** Curium (247) $[Rn]5f^76d7s^2$ 5.9914	97 $^6H^\circ_{15/2}$ **Bk** Berkelium (247) $[Rn]5f^97s^2$ 6.1978	98 $^5I_8$ **Cf** Californium (251) $[Rn]5f^{10}7s^2$ 6.2817	99 $^4I^\circ_{15/2}$ **Es** Einsteinium (252) $[Rn]5f^{11}7s^2$ 6.3676	100 $^3H_6$ **Fm** Fermium (257) $[Rn]5f^{12}7s^2$ 6.50	101 $^2F^\circ_{7/2}$ **Md** Mendelevium (258) $[Rn]5f^{13}7s^2$ 6.58	102 $^1S_0$ **No** Nobelium (259) $[Rn]5f^{14}7s^2$ 6.65	103 $^2P^\circ_{1/2}$ **Lr** Lawrencium (262) $[Rn]5f^{14}7s^27p$ 4.90

Atomic Number: 58
Ground-state Level: $^1G^\circ_4$
Symbol: **Ce**
Name: Cerium
Standard Atomic Weight†: 140.116
Ground-state Configuration: $[Xe]4f5d6s^2$
Ionization Energy (eV): 5.5386

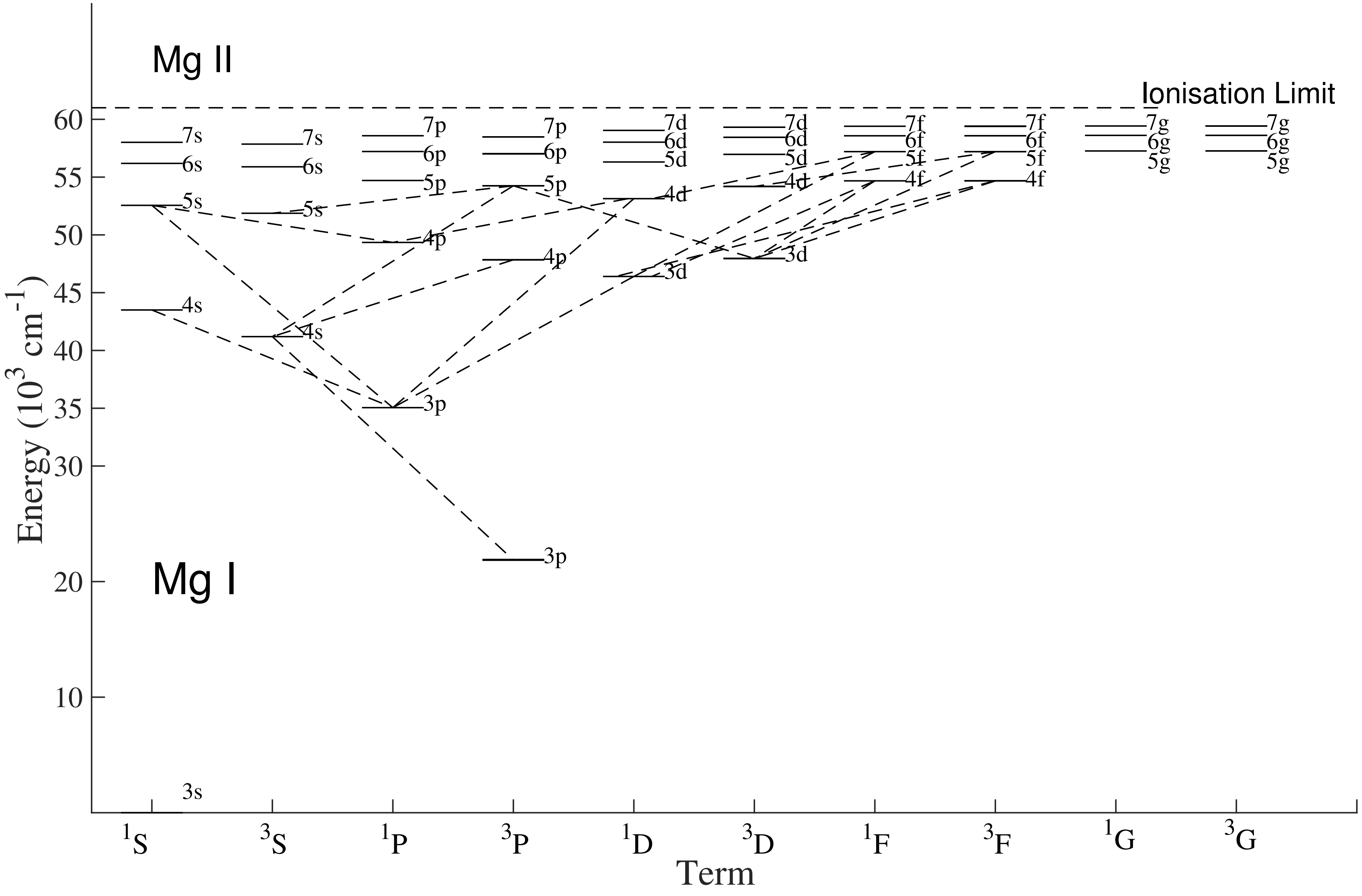
†Based upon ^{12}C. () indicates the mass number of the longest-lived isotope.

*IUPAC conventional atomic weights; standard atomic weights for these elements are expressed in intervals; see iupac.org for an explanation and values.

For a description of the data, visit physics.nist.gov/data

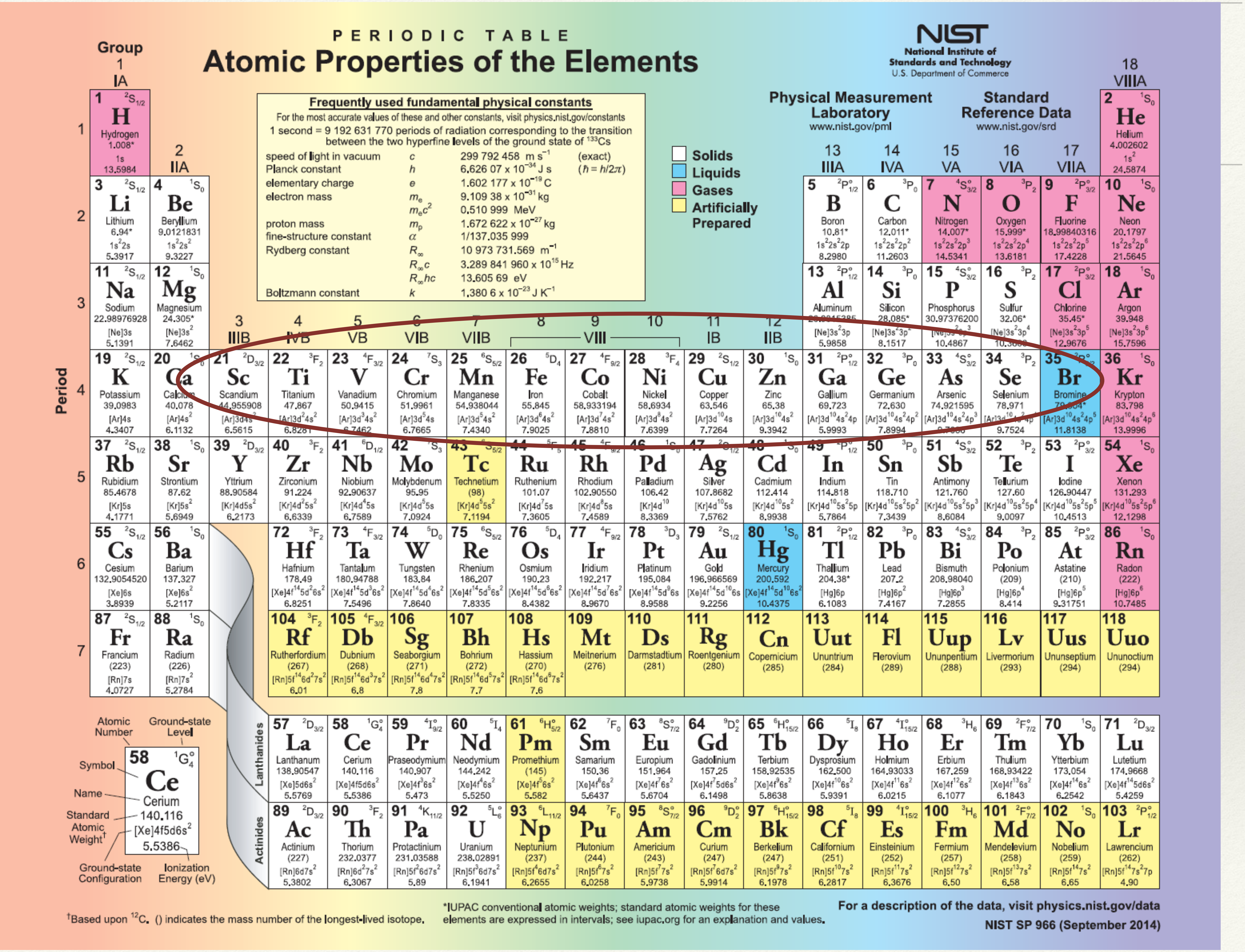
NIST SP 966 (September 2014)

Magnesium



Burheim et al. (2023)

$10\,000\ \text{cm}^{-1} = 1$ micron



PERIODIC TABLE

Atomic Properties of the Elements

NIST
National Institute of Standards and Technology
U.S. Department of Commerce

Physical Measurement Laboratory
www.nist.gov/pml

Standard Reference Data
www.nist.gov/srd

Frequently used fundamental physical constants

For the most accurate values of these and other constants, visit physics.nist.gov/constants

1 second = 9 192 631 770 periods of radiation corresponding to the transition between the two hyperfine levels of the ground state of ^{133}Cs

speed of light in vacuum	c	299 792 458 m s^{-1}	(exact)
Planck constant	h	6.626 07 x 10^{-34} J s	($\hbar = h/2\pi$)
elementary charge	e	1.602 177 x 10^{-19} C	
electron mass	m_e	9.109 38 x 10^{-31} kg	
	m_ec^2	0.510 999 MeV	
proton mass	m_p	1.672 622 x 10^{-27} kg	
fine-structure constant	α	1/137.035 999	
Rydberg constant	R_∞	10 973 731.569 m^{-1}	
	$R_\infty c$	3.289 841 960 x 10^{15} Hz	
	$R_\infty hc$	13.605 69 eV	
Boltzmann constant	k	1.380 6 x 10^{-23} J K^{-1}	

⬜ Solids
🟦 Liquids
🟪 Gases
🟨 Artificially Prepared

Period	Group 1 IA	2 IIA	3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8	9 VIII	10	11 IB	12 IIB	13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	18 VIIIA
1	1 $^2S_{1/2}$ **H** Hydrogen 1.008* 1s 13.5984																	2 $^1S_0$ **He** Helium 4.002602 $1s^2$ 24.5874
2	3 $^2S_{1/2}$ **Li** Lithium 6.94* $1s^22s$ 5.3917	4 $^1S_0$ **Be** Beryllium 9.0121831 $1s^22s^2$ 9.3227											5 $^2P^\circ_{1/2}$ **B** Boron 10.81* $1s^22s^22p$ 8.2980	6 $^3P_0$ **C** Carbon 12.011* $1s^22s^22p^2$ 11.2603	7 $^4S^\circ_{3/2}$ **N** Nitrogen 14.007* $1s^22s^22p^3$ 14.5341	8 $^3P_2$ **O** Oxygen 15.999* $1s^22s^22p^4$ 13.6181	9 $^2P^\circ_{3/2}$ **F** Fluorine 18.99840316 $1s^22s^22p^5$ 17.4228	10 $^1S_0$ **Ne** Neon 20.1797 $1s^22s^22p^6$ 21.5645
3	11 $^2S_{1/2}$ **Na** Sodium 22.98976928 [Ne]3s 5.1391	12 $^1S_0$ **Mg** Magnesium 24.305* [Ne]$3s^2$ 7.6462											13 $^2P^\circ_{1/2}$ **Al** Aluminum 26.9815385 [Ne]$3s^23p$ 5.9858	14 $^3P_0$ **Si** Silicon 28.085* [Ne]$3s^23p^2$ 8.1517	15 $^4S^\circ_{3/2}$ **P** Phosphorus 30.97376200 [Ne]$3s^23p^3$ 10.4867	16 $^3P_2$ **S** Sulfur 32.06* [Ne]$3s^23p^4$ 10.3600	17 $^2P^\circ_{3/2}$ **Cl** Chlorine 35.45* [Ne]$3s^23p^5$ 12.9676	18 $^1S_0$ **Ar** Argon 39.948 [Ne]$3s^23p^6$ 15.7596
4	19 $^2S_{1/2}$ **K** Potassium 39.0983 [Ar]4s 4.3407	20 $^1S_0$ **Ca** Calcium 40.078 [Ar]$4s^2$ 6.1132	21 $^2D_{3/2}$ **Sc** Scandium 44.955908 [Ar]$3d4s^2$ 6.5615	22 $^3F_2$ **Ti** Titanium 47.867 [Ar]$3d^24s^2$ 6.8281	23 $^4F_{3/2}$ **V** Vanadium 50.9415 [Ar]$3d^34s^2$ 6.7462	24 $^7S_3$ **Cr** Chromium 51.9961 [Ar]$3d^54s$ 6.7665	25 $^6S_{5/2}$ **Mn** Manganese 54.938044 [Ar]$3d^54s^2$ 7.4340	26 $^5D_4$ **Fe** Iron 55.845 [Ar]$3d^64s^2$ 7.9025	27 $^4F_{9/2}$ **Co** Cobalt 58.933194 [Ar]$3d^74s^2$ 7.8810	28 $^3F_4$ **Ni** Nickel 58.6934 [Ar]$3d^84s^2$ 7.6399	29 $^2S_{1/2}$ **Cu** Copper 63.546 [Ar]$3d^{10}4s$ 7.7264	30 $^1S_0$ **Zn** Zinc 65.38 [Ar]$3d^{10}4s^2$ 9.3942	31 $^2P^\circ_{1/2}$ **Ga** Gallium 69.723 [Ar]$3d^{10}4s^24p$ 5.9993	32 $^3P_0$ **Ge** Germanium 72.630 [Ar]$3d^{10}4s^24p^2$ 7.8994	33 $^4S^\circ_{3/2}$ **As** Arsenic 74.921595 [Ar]$3d^{10}4s^24p^3$ 9.7886	34 $^3P_2$ **Se** Selenium 78.971 [Ar]$3d^{10}4s^24p^4$ 9.7524	35 $^2P^\circ_{3/2}$ **Br** Bromine 79.904* [Ar]$3d^{10}4s^24p^5$ 11.8138	36 $^1S_0$ **Kr** Krypton 83.798 [Ar]$3d^{10}4s^24p^6$ 13.9996
5	37 $^2S_{1/2}$ **Rb** Rubidium 85.4678 [Kr]5s 4.1771	38 $^1S_0$ **Sr** Strontium 87.62 [Kr]$5s^2$ 5.6949	39 $^2D_{3/2}$ **Y** Yttrium 88.90584 [Kr]$4d5s^2$ 6.2173	40 $^3F_2$ **Zr** Zirconium 91.224 [Kr]$4d^25s^2$ 6.6339	41 $^6D_{1/2}$ **Nb** Niobium 92.90637 [Kr]$4d^45s$ 6.7589	42 $^7S_3$ **Mo** Molybdenum 95.95 [Kr]$4d^55s$ 7.0924	43 $^6S_{5/2}$ **Tc** Technetium (98) [Kr]$4d^55s^2$ 7.1194	44 $^5F_5$ **Ru** Ruthenium 101.07 [Kr]$4d^75s$ 7.3605	45 $^4F_{9/2}$ **Rh** Rhodium 102.90550 [Kr]$4d^85s$ 7.4589	46 $^1S_0$ **Pd** Palladium 106.42 [Kr]$4d^{10}$ 8.3369	47 $^2S_{1/2}$ **Ag** Silver 107.8682 [Kr]$4d^{10}5s$ 7.5762	48 $^1S_0$ **Cd** Cadmium 112.414 [Kr]$4d^{10}5s^2$ 8.9938	49 $^2P^\circ_{1/2}$ **In** Indium 114.818 [Kr]$4d^{10}5s^25p$ 5.7864	50 $^3P_0$ **Sn** Tin 118.710 [Kr]$4d^{10}5s^25p^2$ 7.3439	51 $^4S^\circ_{3/2}$ **Sb** Antimony 121.760 [Kr]$4d^{10}5s^25p^3$ 8.6084	52 $^3P_2$ **Te** Tellurium 127.60 [Kr]$4d^{10}5s^25p^4$ 9.0097	53 $^2P^\circ_{3/2}$ **I** Iodine 126.90447 [Kr]$4d^{10}5s^25p^5$ 10.4513	54 $^1S_0$ **Xe** Xenon 131.293 [Kr]$4d^{10}5s^25p^6$ 12.1298
6	55 $^2S_{1/2}$ **Cs** Cesium 132.9054520 [Xe]6s 3.8939	56 $^1S_0$ **Ba** Barium 137.327 [Xe]$6s^2$ 5.2117		72 $^3F_2$ **Hf** Hafnium 178.49 [Xe]$4f^{14}5d^26s^2$ 6.8251	73 $^4F_{3/2}$ **Ta** Tantalum 180.94788 [Xe]$4f^{14}5d^36s^2$ 7.5496	74 $^5D_0$ **W** Tungsten 183.84 [Xe]$4f^{14}5d^46s^2$ 7.8640	75 $^6S_{5/2}$ **Re** Rhenium 186.207 [Xe]$4f^{14}5d^56s^2$ 7.8335	76 $^5D_4$ **Os** Osmium 190.23 [Xe]$4f^{14}5d^66s^2$ 8.4382	77 $^4F_{9/2}$ **Ir** Iridium 192.217 [Xe]$4f^{14}5d^76s^2$ 8.9670	78 $^3D_3$ **Pt** Platinum 195.084 [Xe]$4f^{14}5d^96s$ 8.9588	79 $^2S_{1/2}$ **Au** Gold 196.966569 [Xe]$4f^{14}5d^{10}6s$ 9.2256	80 $^1S_0$ **Hg** Mercury 200.592 [Xe]$4f^{14}5d^{10}6s^2$ 10.4375	81 $^2P^\circ_{1/2}$ **Tl** Thallium 204.38* [Hg]6p 6.1083	82 $^3P_0$ **Pb** Lead 207.2 [Hg]$6p^2$ 7.4167	83 $^4S^\circ_{3/2}$ **Bi** Bismuth 208.98040 [Hg]$6p^3$ 7.2855	84 $^3P_2$ **Po** Polonium (209) [Hg]$6p^4$ 8.414	85 $^2P^\circ_{3/2}$ **At** Astatine (210) [Hg]$6p^5$ 9.31751	86 $^1S_0$ **Rn** Radon (222) [Hg]$6p^6$ 10.7485
7	87 $^2S_{1/2}$ **Fr** Francium (223) [Rn]7s 4.0727	88 $^1S_0$ **Ra** Radium (226) [Rn]$7s^2$ 5.2784		104 $^3F_2$ **Rf** Rutherfordium (267) [Rn]$5f^{14}6d^27s^2$ 6.01	105 $^4F_{3/2}$ **Db** Dubnium (268) [Rn]$5f^{14}6d^37s^2$ 6.8	106 **Sg** Seaborgium (271) [Rn]$5f^{14}6d^47s^2$ 7.8	107 **Bh** Bohrium (272) [Rn]$5f^{14}6d^57s^2$ 7.7	108 **Hs** Hassium (270) [Rn]$5f^{14}6d^67s^2$ 7.6	109 **Mt** Meitnerium (276)	110 **Ds** Darmstadtium (281)	111 **Rg** Roentgenium (280)	112 **Cn** Copernicium (285)	113 **Uut** Ununtrium (284)	114 **Fl** Flerovium (289)	115 **Uup** Ununpentium (288)	116 **Lv** Livermorium (293)	117 **Uus** Ununseptium (294)	118 **Uuo** Ununoctium (294)

Lanthanides	57 $^2D_{3/2}$ **La** Lanthanum 138.90547 [Xe]$5d6s^2$ 5.5769	58 $^1G^\circ_4$ **Ce** Cerium 140.116 [Xe]$4f5d6s^2$ 5.5386	59 $^4I^\circ_{9/2}$ **Pr** Praseodymium 140.907 [Xe]$4f^36s^2$ 5.473	60 $^5I_4$ **Nd** Neodymium 144.242 [Xe]$4f^46s^2$ 5.5250	61 $^6H^\circ_{5/2}$ **Pm** Promethium (145) [Xe]$4f^56s^2$ 5.582	62 $^7F_0$ **Sm** Samarium 150.36 [Xe]$4f^66s^2$ 5.6437	63 $^8S^\circ_{7/2}$ **Eu** Europium 151.964 [Xe]$4f^76s^2$ 5.6704	64 $^9D^\circ_2$ **Gd** Gadolinium 157.25 [Xe]$4f^75d6s^2$ 6.1498	65 $^6H^\circ_{15/2}$ **Tb** Terbium 158.92535 [Xe]$4f^96s^2$ 5.8638	66 $^5I_8$ **Dy** Dysprosium 162.500 [Xe]$4f^{10}6s^2$ 5.9391	67 $^4I^\circ_{15/2}$ **Ho** Holmium 164.93033 [Xe]$4f^{11}6s^2$ 6.0215	68 $^3H_6$ **Er** Erbium 167.259 [Xe]$4f^{12}6s^2$ 6.1077	69 $^2F^\circ_{7/2}$ **Tm** Thulium 168.93422 [Xe]$4f^{13}6s^2$ 6.1843	70 $^1S_0$ **Yb** Ytterbium 173.054 [Xe]$4f^{14}6s^2$ 6.2542	71 $^2D_{3/2}$ **Lu** Lutetium 174.9668 [Xe]$4f^{14}5d6s^2$ 5.4259
Actinides	89 $^2D_{3/2}$ **Ac** Actinium (227) [Rn]$6d7s^2$ 5.3802	90 $^3F_2$ **Th** Thorium 232.0377 [Rn]$6d^27s^2$ 6.3067	91 $^4K_{11/2}$ **Pa** Protactinium 231.03588 [Rn]$5f^26d7s^2$ 5.89	92 $^5L^\circ_6$ **U** Uranium 238.02891 [Rn]$5f^36d7s^2$ 6.1941	93 $^6L_{11/2}$ **Np** Neptunium (237) [Rn]$5f^46d7s^2$ 6.2655	94 $^7F_0$ **Pu** Plutonium (244) [Rn]$5f^67s^2$ 6.0258	95 $^8S^\circ_{7/2}$ **Am** Americium (243) [Rn]$5f^77s^2$ 5.9738	96 $^9D^\circ_2$ **Cm** Curium (247) [Rn]$5f^76d7s^2$ 5.9914	97 $^6H^\circ_{15/2}$ **Bk** Berkelium (247) [Rn]$5f^97s^2$ 6.1978	98 $^5I_8$ **Cf** Californium (251) [Rn]$5f^{10}7s^2$ 6.2817	99 $^4I^\circ_{15/2}$ **Es** Einsteinium (252) [Rn]$5f^{11}7s^2$ 6.3676	100 $^3H_6$ **Fm** Fermium (257) [Rn]$5f^{12}7s^2$ 6.50	101 $^2F^\circ_{7/2}$ **Md** Mendelevium (258) [Rn]$5f^{13}7s^2$ 6.58	102 $^1S_0$ **No** Nobelium (259) [Rn]$5f^{14}7s^2$ 6.65	103 $^2P^\circ_{1/2}$ **Lr** Lawrencium (262) [Rn]$5f^{14}7s^27p$ 4.90

Atomic Number — 58
Ground-state Level — $^1G^\circ_4$
Symbol — **Ce**
Name — Cerium
Standard Atomic Weight[†] — 140.116
Ground-state Configuration — [Xe]$4f5d6s^2$
Ionization Energy (eV) — 5.5386

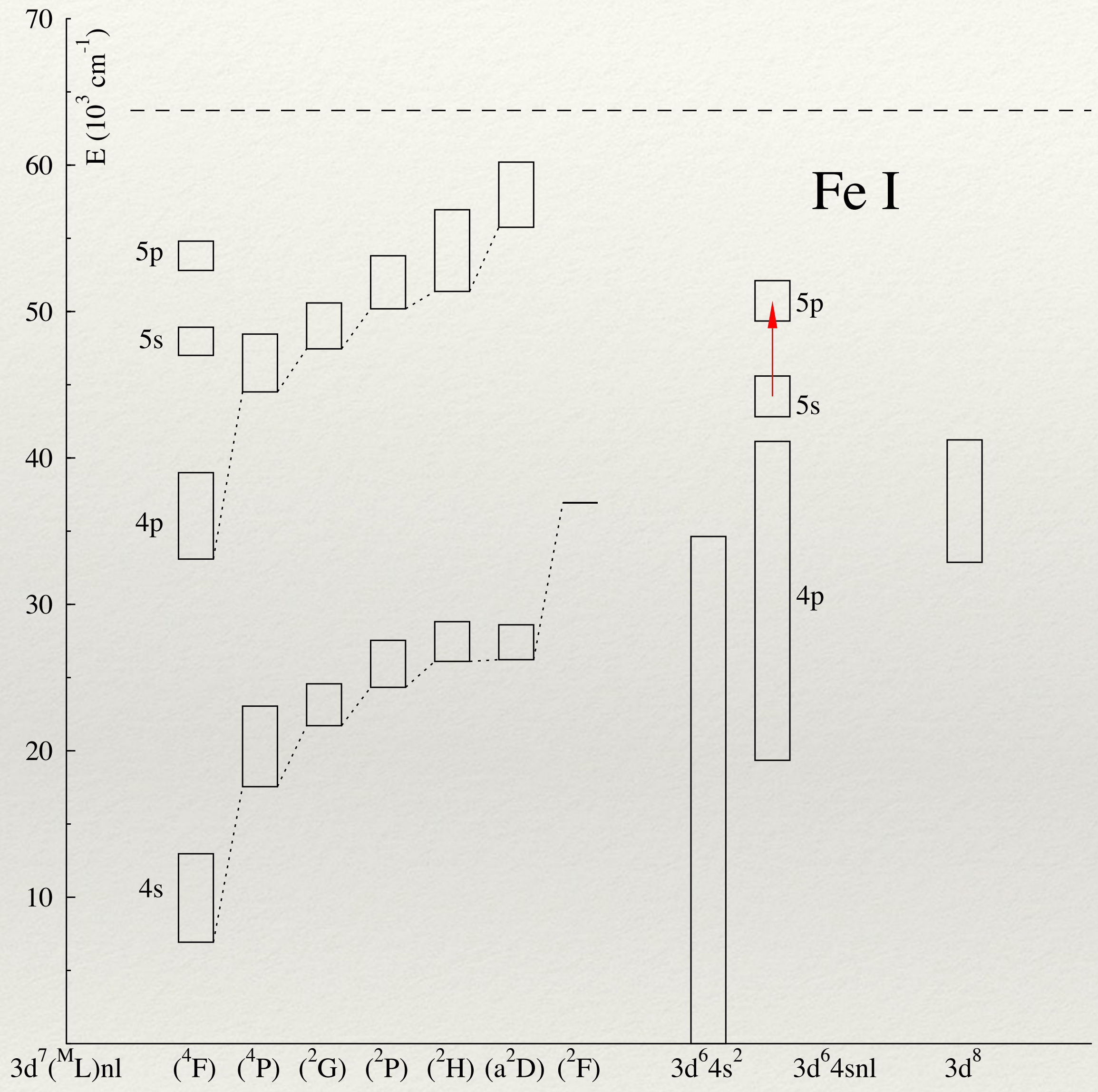
[†] Based upon ^{12}C. () indicates the mass number of the longest-lived isotope.

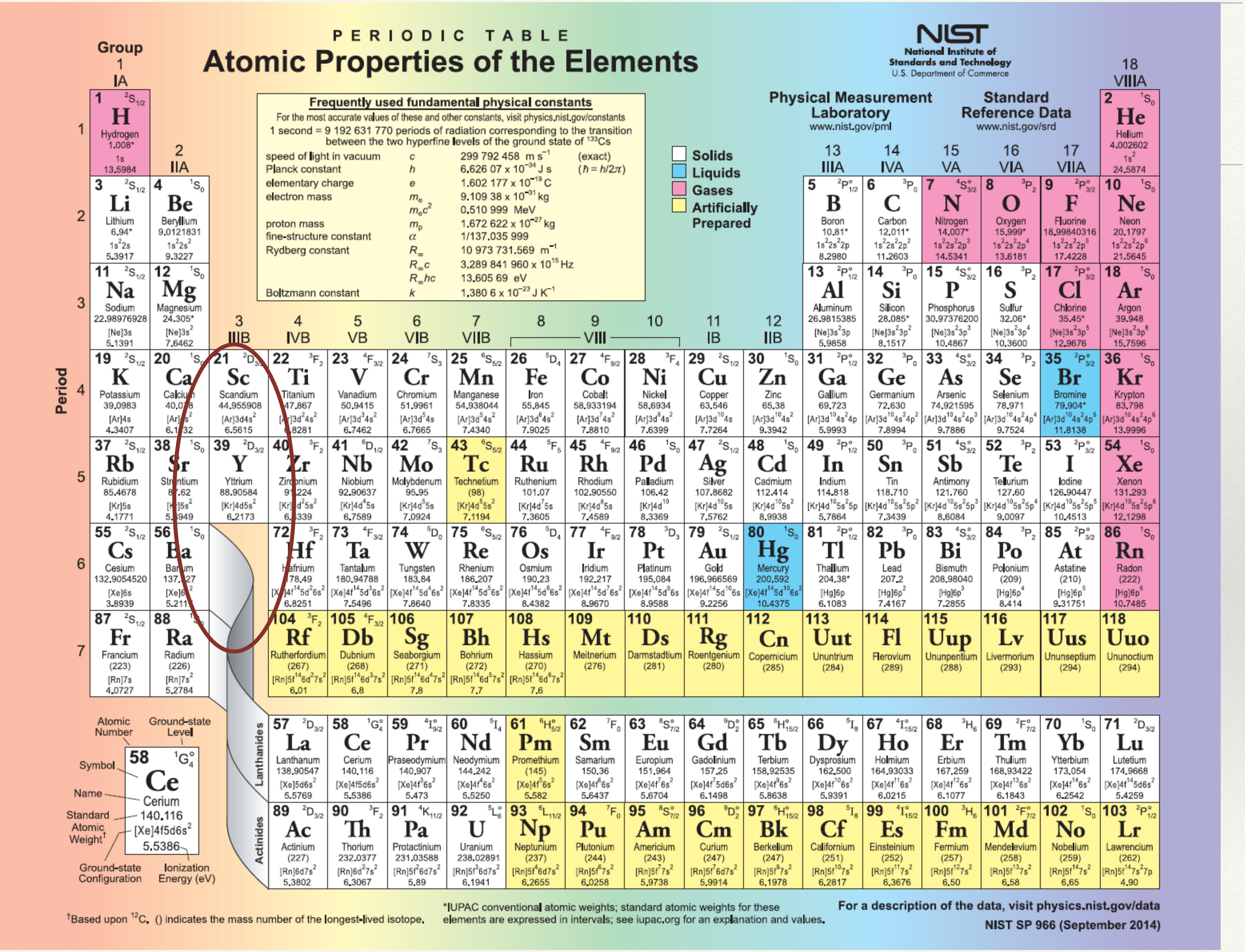
*IUPAC conventional atomic weights; standard atomic weights for these elements are expressed in intervals; see iupac.org for an explanation and values.

For a description of the data, visit physics.nist.gov/data

NIST SP 966 (September 2014)

High-excitation states in Fe-group





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elementary charge	e	1.602 177 x 10^{-19} C	
electron mass	m_e	9.109 38 x 10^{-31} kg	
	m_ec^2	0.510 999 MeV	
proton mass	m_p	1.672 622 x 10^{-27} kg	
fine-structure constant	α	1/137.035 999	
Rydberg constant	R_∞	10 973 731.569 m^{-1}	
	$R_\infty c$	3.289 841 960 x 10^{15} Hz	
	$R_\infty hc$	13.605 69 eV	
Boltzmann constant	k	1.380 6 x 10^{-23} J K^{-1}	

☐ Solids
🟦 Liquids
🟥 Gases
🟨 Artificially Prepared

Period	Group 1 IA	2 IIA	3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8 VIII	9 VIII	10 VIII	11 IB	12 IIB	13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	18 VIIIA
1	1 $^{2}S_{1/2}$ **H** Hydrogen 1.008* $1s$ 13.5984																	2 $^{1}S_{0}$ **He** Helium 4.002602 $1s^{2}$ 24.5874
2	3 $^{2}S_{1/2}$ **Li** Lithium 6.94* $1s^{2}2s$ 5.3917	4 $^{1}S_{0}$ **Be** Beryllium 9.0121831 $1s^{2}2s^{2}$ 9.3227											5 $^{2}P^{\circ}_{1/2}$ **B** Boron 10.81* $1s^{2}2s^{2}2p$ 8.2980	6 $^{3}P_{0}$ **C** Carbon 12.011* $1s^{2}2s^{2}2p^{2}$ 11.2603	7 $^{4}S^{\circ}_{3/2}$ **N** Nitrogen 14.007* $1s^{2}2s^{2}2p^{3}$ 14.5341	8 $^{3}P_{2}$ **O** Oxygen 15.999* $1s^{2}2s^{2}2p^{4}$ 13.6181	9 $^{2}P^{\circ}_{3/2}$ **F** Fluorine 18.99840316 $1s^{2}2s^{2}2p^{5}$ 17.4228	10 $^{1}S_{0}$ **Ne** Neon 20.1797 $1s^{2}2s^{2}2p^{6}$ 21.5645
3	11 $^{2}S_{1/2}$ **Na** Sodium 22.98976928 [Ne]$3s$ 5.1391	12 $^{1}S_{0}$ **Mg** Magnesium 24.305* [Ne]$3s^{2}$ 7.6462											13 $^{2}P^{\circ}_{1/2}$ **Al** Aluminum 26.9815385 [Ne]$3s^{2}3p$ 5.9858	14 $^{3}P_{0}$ **Si** Silicon 28.085* [Ne]$3s^{2}3p^{2}$ 8.1517	15 $^{4}S^{\circ}_{3/2}$ **P** Phosphorus 30.97376200 [Ne]$3s^{2}3p^{3}$ 10.4867	16 $^{3}P_{2}$ **S** Sulfur 32.06* [Ne]$3s^{2}3p^{4}$ 10.3600	17 $^{2}P^{\circ}_{3/2}$ **Cl** Chlorine 35.45* [Ne]$3s^{2}3p^{5}$ 12.9676	18 $^{1}S_{0}$ **Ar** Argon 39.948 [Ne]$3s^{2}3p^{6}$ 15.7596
4	19 $^{2}S_{1/2}$ **K** Potassium 39.0983 [Ar]$4s$ 4.3407	20 $^{1}S_{0}$ **Ca** Calcium 40.078 [Ar]$4s^{2}$ 6.1132	21 $^{2}D_{3/2}$ **Sc** Scandium 44.955908 [Ar]$3d4s^{2}$ 6.5615	22 $^{3}F_{2}$ **Ti** Titanium 47.867 [Ar]$3d^{2}4s^{2}$ 6.8281	23 $^{4}F_{3/2}$ **V** Vanadium 50.9415 [Ar]$3d^{3}4s^{2}$ 6.7462	24 $^{7}S_{3}$ **Cr** Chromium 51.9961 [Ar]$3d^{5}4s$ 6.7665	25 $^{6}S_{5/2}$ **Mn** Manganese 54.938044 [Ar]$3d^{5}4s^{2}$ 7.4340	26 $^{5}D_{4}$ **Fe** Iron 55.845 [Ar]$3d^{6}4s^{2}$ 7.9025	27 $^{4}F_{9/2}$ **Co** Cobalt 58.933194 [Ar]$3d^{7}4s^{2}$ 7.8810	28 $^{3}F_{4}$ **Ni** Nickel 58.6934 [Ar]$3d^{8}4s^{2}$ 7.6399	29 $^{2}S_{1/2}$ **Cu** Copper 63.546 [Ar]$3d^{10}4s$ 7.7264	30 $^{1}S_{0}$ **Zn** Zinc 65.38 [Ar]$3d^{10}4s^{2}$ 9.3942	31 $^{2}P^{\circ}_{1/2}$ **Ga** Gallium 69.723 [Ar]$3d^{10}4s^{2}4p$ 5.9993	32 $^{3}P_{0}$ **Ge** Germanium 72.630 [Ar]$3d^{10}4s^{2}4p^{2}$ 7.8994	33 $^{4}S^{\circ}_{3/2}$ **As** Arsenic 74.921595 [Ar]$3d^{10}4s^{2}4p^{3}$ 9.7886	34 $^{3}P_{2}$ **Se** Selenium 78.971 [Ar]$3d^{10}4s^{2}4p^{4}$ 9.7524	35 $^{2}P^{\circ}_{3/2}$ **Br** Bromine 79.904* [Ar]$3d^{10}4s^{2}4p^{5}$ 11.8138	36 $^{1}S_{0}$ **Kr** Krypton 83.798 [Ar]$3d^{10}4s^{2}4p^{6}$ 13.9996
5	37 $^{2}S_{1/2}$ **Rb** Rubidium 85.4678 [Kr]$5s$ 4.1771	38 $^{1}S_{0}$ **Sr** Strontium 87.62 [Kr]$5s^{2}$ 5.6949	39 $^{2}D_{3/2}$ **Y** Yttrium 88.90584 [Kr]$4d5s^{2}$ 6.2173	40 $^{3}F_{2}$ **Zr** Zirconium 91.224 [Kr]$4d^{2}5s^{2}$ 6.6339	41 $^{6}D_{1/2}$ **Nb** Niobium 92.90637 [Kr]$4d^{4}5s$ 6.7589	42 $^{7}S_{3}$ **Mo** Molybdenum 95.95 [Kr]$4d^{5}5s$ 7.0924	43 $^{6}S_{5/2}$ **Tc** Technetium (98) [Kr]$4d^{5}5s^{2}$ 7.1194	44 $^{5}F_{5}$ **Ru** Ruthenium 101.07 [Kr]$4d^{7}5s$ 7.3605	45 $^{4}F_{9/2}$ **Rh** Rhodium 102.90550 [Kr]$4d^{8}5s$ 7.4589	46 $^{1}S_{0}$ **Pd** Palladium 106.42 [Kr]$4d^{10}$ 8.3369	47 $^{2}S_{1/2}$ **Ag** Silver 107.8682 [Kr]$4d^{10}5s$ 7.5762	48 $^{1}S_{0}$ **Cd** Cadmium 112.414 [Kr]$4d^{10}5s^{2}$ 8.9938	49 $^{2}P^{\circ}_{1/2}$ **In** Indium 114.818 [Kr]$4d^{10}5s^{2}5p$ 5.7864	50 $^{3}P_{0}$ **Sn** Tin 118.710 [Kr]$4d^{10}5s^{2}5p^{2}$ 7.3439	51 $^{4}S^{\circ}_{3/2}$ **Sb** Antimony 121.760 [Kr]$4d^{10}5s^{2}5p^{3}$ 8.6084	52 $^{3}P_{2}$ **Te** Tellurium 127.60 [Kr]$4d^{10}5s^{2}5p^{4}$ 9.0097	53 $^{2}P^{\circ}_{3/2}$ **I** Iodine 126.90447 [Kr]$4d^{10}5s^{2}5p^{5}$ 10.4513	54 $^{1}S_{0}$ **Xe** Xenon 131.293 [Kr]$4d^{10}5s^{2}5p^{6}$ 12.1298
6	55 $^{2}S_{1/2}$ **Cs** Cesium 132.9054520 [Xe]$6s$ 3.8939	56 $^{1}S_{0}$ **Ba** Barium 137.327 [Xe]$6s^{2}$ 5.2117		72 $^{3}F_{2}$ **Hf** Hafnium 178.49 [Xe]$4f^{14}5d^{2}6s^{2}$ 6.8251	73 $^{4}F_{3/2}$ **Ta** Tantalum 180.94788 [Xe]$4f^{14}5d^{3}6s^{2}$ 7.5496	74 $^{5}D_{0}$ **W** Tungsten 183.84 [Xe]$4f^{14}5d^{4}6s^{2}$ 7.8640	75 $^{6}S_{5/2}$ **Re** Rhenium 186.207 [Xe]$4f^{14}5d^{5}6s^{2}$ 7.8335	76 $^{5}D_{4}$ **Os** Osmium 190.23 [Xe]$4f^{14}5d^{6}6s^{2}$ 8.4382	77 $^{4}F_{9/2}$ **Ir** Iridium 192.217 [Xe]$4f^{14}5d^{7}6s^{2}$ 8.9670	78 $^{3}D_{3}$ **Pt** Platinum 195.084 [Xe]$4f^{14}5d^{9}6s$ 8.9588	79 $^{2}S_{1/2}$ **Au** Gold 196.966569 [Xe]$4f^{14}5d^{10}6s$ 9.2256	80 $^{1}S_{0}$ **Hg** Mercury 200.592 [Xe]$4f^{14}5d^{10}6s^{2}$ 10.4375	81 $^{2}P^{\circ}_{1/2}$ **Tl** Thallium 204.38* [Hg]$6p$ 6.1083	82 $^{3}P_{0}$ **Pb** Lead 207.2 [Hg]$6p^{2}$ 7.4167	83 $^{4}S^{\circ}_{3/2}$ **Bi** Bismuth 208.98040 [Hg]$6p^{3}$ 7.2855	84 $^{3}P_{2}$ **Po** Polonium (209) [Hg]$6p^{4}$ 8.414	85 $^{2}P^{\circ}_{3/2}$ **At** Astatine (210) [Hg]$6p^{5}$ 9.31751	86 $^{1}S_{0}$ **Rn** Radon (222) [Hg]$6p^{6}$ 10.7485
7	87 $^{2}S_{1/2}$ **Fr** Francium (223) [Rn]$7s$ 4.0727	88 $^{1}S_{0}$ **Ra** Radium (226) [Rn]$7s^{2}$ 5.2784		104 $^{3}F_{2}$ **Rf** Rutherfordium (267) [Rn]$5f^{14}6d^{2}7s^{2}$ 6.01	105 $^{4}F_{3/2}$ **Db** Dubnium (268) [Rn]$5f^{14}6d^{3}7s^{2}$ 6.8	106 **Sg** Seaborgium (271) [Rn]$5f^{14}6d^{4}7s^{2}$ 7.8	107 **Bh** Bohrium (272) [Rn]$5f^{14}6d^{5}7s^{2}$ 7.7	108 **Hs** Hassium (270) [Rn]$5f^{14}6d^{6}7s^{2}$ 7.6	109 **Mt** Meitnerium (276)	110 **Ds** Darmstadtium (281)	111 **Rg** Roentgenium (280)	112 **Cn** Copernicium (285)	113 **Uut** Ununtrium (284)	114 **Fl** Flerovium (289)	115 **Uup** Ununpentium (288)	116 **Lv** Livermorium (293)	117 **Uus** Ununseptium (294)	118 **Uuo** Ununoctium (294)

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Atomic Number — 58
Ground-state Level — $^{1}G^{\circ}_{4}$
Symbol — **Ce**
Name — Cerium
Standard Atomic Weight† — 140.116
Ground-state Configuration — [Xe]$4f5d6s^{2}$
Ionization Energy (eV) — 5.5386

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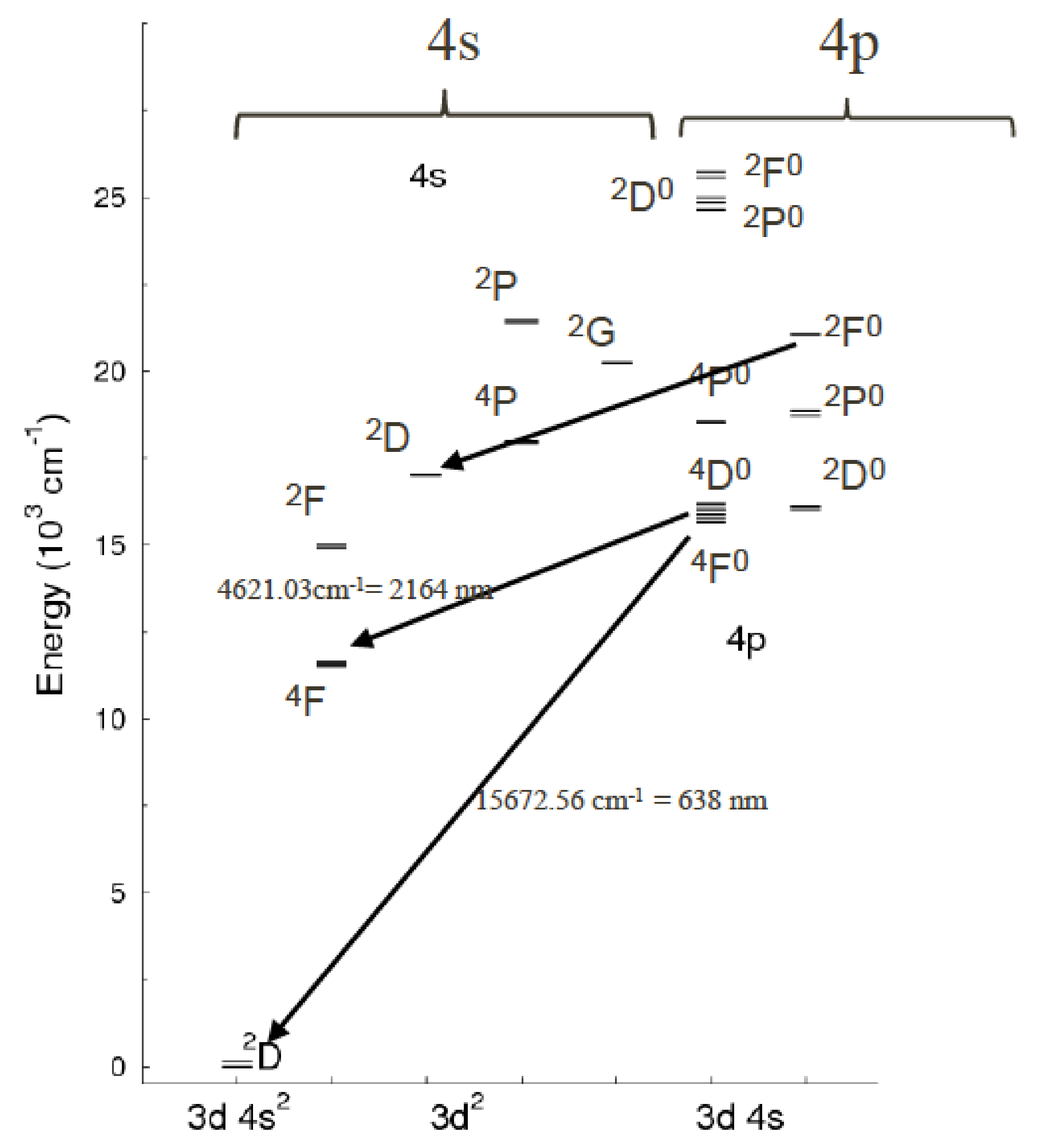
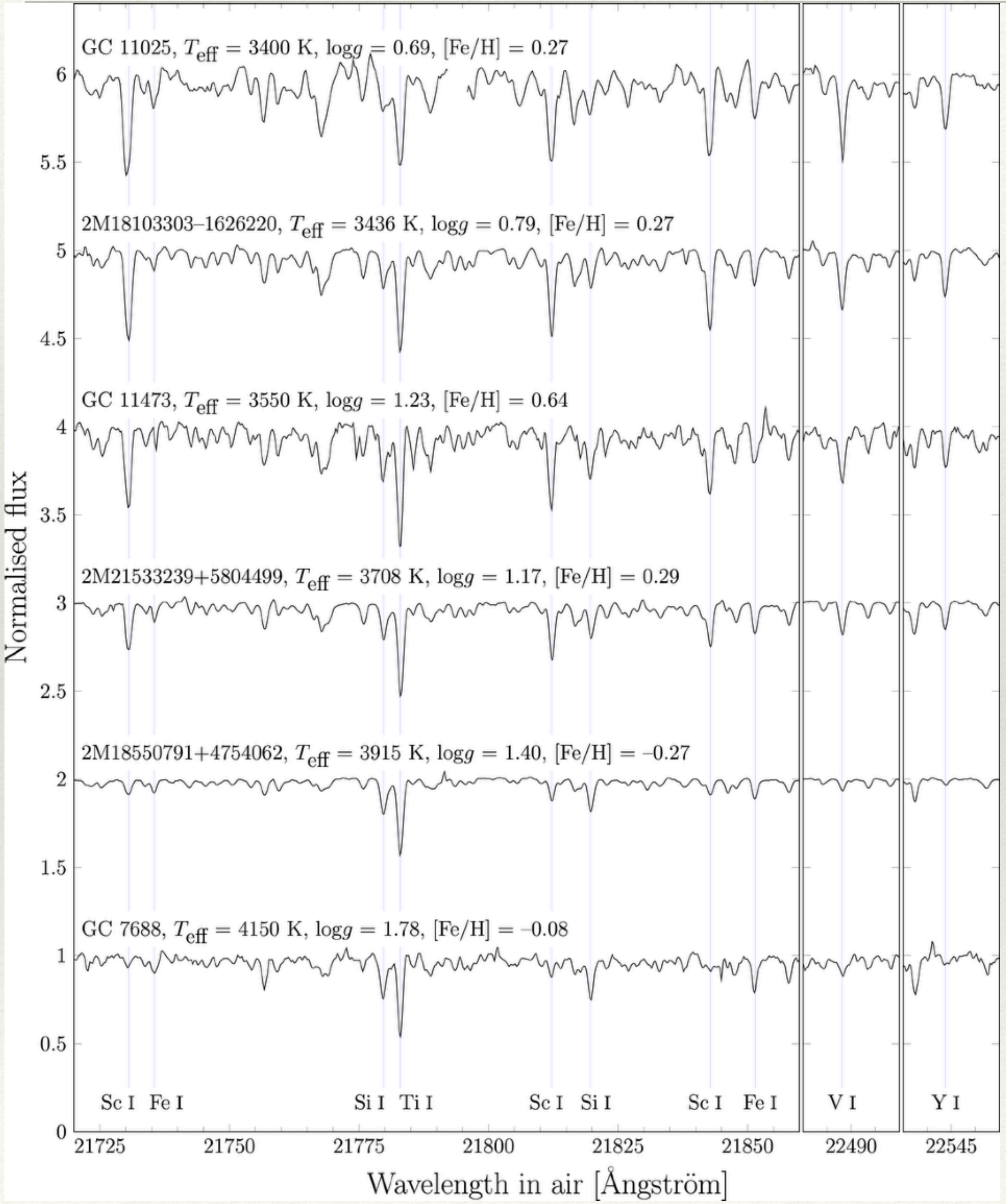
Sc I, Y I and La I



The energy level structure of Sc I, Y I and La I are similar with the energy levels for $nd(n+1)s^2$ and $nd^2(n+1)s$

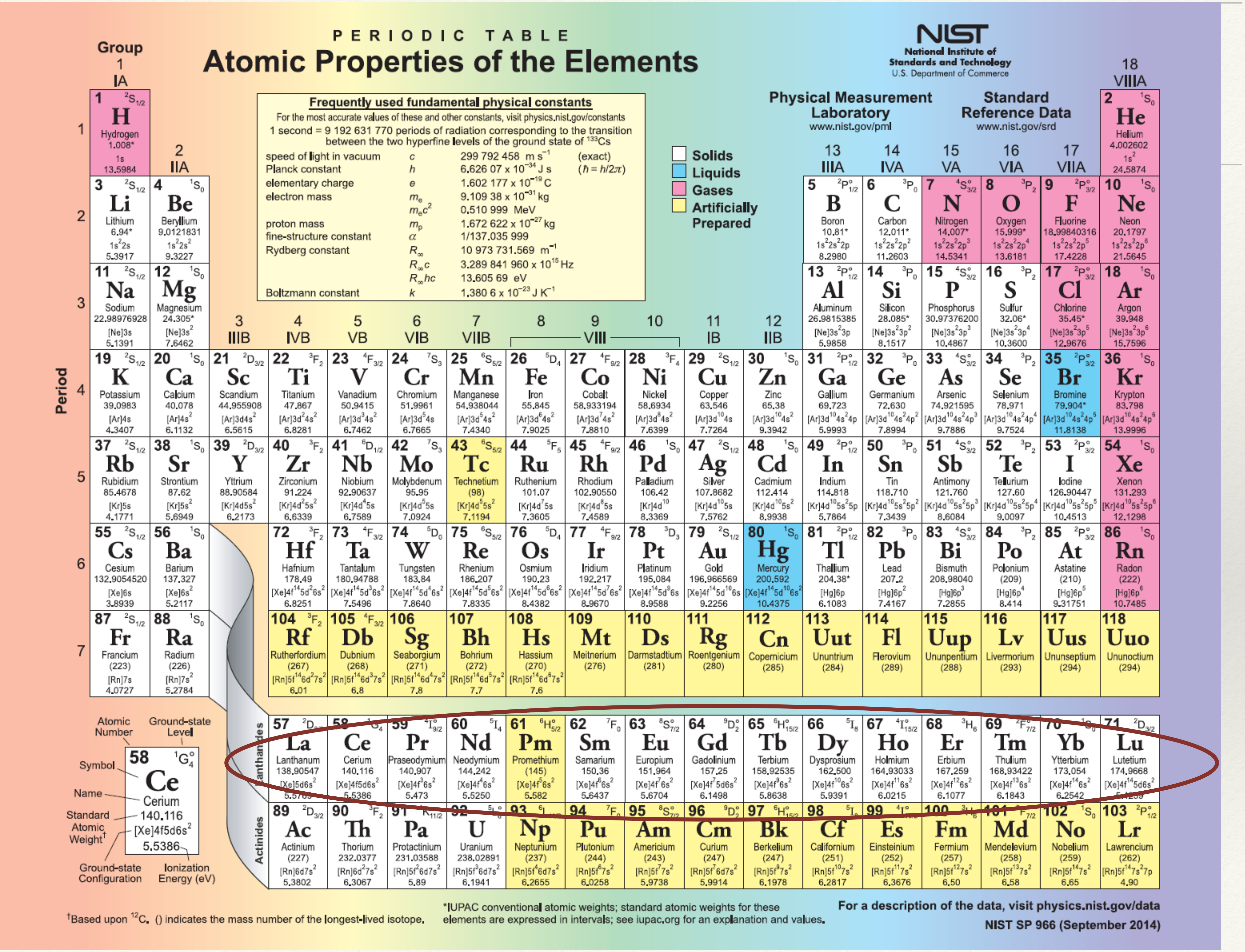
Sc I : $3d4s^2$, $3d^24s$
Y I : $4d5s^2$, $4d^25s$
La I : $5d6s^2$, $5d^26s$

Strong lines in infrared of Sc I



Spectra of Galactic center M stars,
Showing strong Sc I and Y I lines, but
Likely due to low excitation rather than
overabundance

Thorsbro et al., 2018 The Astrophysical Journal **866** 52



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1	1 $^2S_{1/2}$ **H** Hydrogen 1.008* 1s 13.5984																	2 $^1S_0$ **He** Helium 4.002602 1s^2 24.5874
2	3 $^2S_{1/2}$ **Li** Lithium 6.94* 1s^{2}2s 5.3917	4 $^1S_0$ **Be** Beryllium 9.0121831 1s^{2}2s^2 9.3227											5 $^2P^\circ_{1/2}$ **B** Boron 10.81* 1s^{2}2s^{2}2p 8.2980	6 $^3P_0$ **C** Carbon 12.011* 1s^{2}2s^{2}2p^2 11.2603	7 $^4S^\circ_{3/2}$ **N** Nitrogen 14.007* 1s^{2}2s^{2}2p^3 14.5341	8 $^3P_2$ **O** Oxygen 15.999* 1s^{2}2s^{2}2p^4 13.6181	9 $^2P^\circ_{3/2}$ **F** Fluorine 18.99840316 1s^{2}2s^{2}2p^5 17.4228	10 $^1S_0$ **Ne** Neon 20.1797 1s^{2}2s^{2}2p^6 21.5645
3	11 $^2S_{1/2}$ **Na** Sodium 22.98976928 [Ne]3s 5.1391	12 $^1S_0$ **Mg** Magnesium 24.305* [Ne]3s^2 7.6462											13 $^2P^\circ_{1/2}$ **Al** Aluminum 26.9815385 [Ne]3s^{2}3p 5.9858	14 $^3P_0$ **Si** Silicon 28.085* [Ne]3s^{2}3p^2 8.1517	15 $^4S^\circ_{3/2}$ **P** Phosphorus 30.97376200 [Ne]3s^{2}3p^3 10.4867	16 $^3P_2$ **S** Sulfur 32.06* [Ne]3s^{2}3p^4 10.3600	17 $^2P^\circ_{3/2}$ **Cl** Chlorine 35.45* [Ne]3s^{2}3p^5 12.9676	18 $^1S_0$ **Ar** Argon 39.948 [Ne]3s^{2}3p^6 15.7596
4	19 $^2S_{1/2}$ **K** Potassium 39.0983 [Ar]4s 4.3407	20 $^1S_0$ **Ca** Calcium 40.078 [Ar]4s^2 6.1132	21 $^2D_{3/2}$ **Sc** Scandium 44.955908 [Ar]3d4s^2 6.5615	22 $^3F_2$ **Ti** Titanium 47.867 [Ar]3d^{2}4s^2 6.8281	23 $^4F_{3/2}$ **V** Vanadium 50.9415 [Ar]3d^{3}4s^2 6.7462	24 $^7S_3$ **Cr** Chromium 51.9961 [Ar]3d^{5}4s 6.7665	25 $^6S_{5/2}$ **Mn** Manganese 54.938044 [Ar]3d^{5}4s^2 7.4340	26 $^5D_4$ **Fe** Iron 55.845 [Ar]3d^{6}4s^2 7.9025	27 $^4F_{9/2}$ **Co** Cobalt 58.933194 [Ar]3d^{7}4s^2 7.8810	28 $^3F_4$ **Ni** Nickel 58.6934 [Ar]3d^{8}4s^2 7.6399	29 $^2S_{1/2}$ **Cu** Copper 63.546 [Ar]3d^{10}4s 7.7264	30 $^1S_0$ **Zn** Zinc 65.38 [Ar]3d^{10}4s^2 9.3942	31 $^2P^\circ_{1/2}$ **Ga** Gallium 69.723 [Ar]3d^{10}4s^{2}4p 5.9993	32 $^3P_0$ **Ge** Germanium 72.630 [Ar]3d^{10}4s^{2}4p^2 7.8994	33 $^4S^\circ_{3/2}$ **As** Arsenic 74.921595 [Ar]3d^{10}4s^{2}4p^3 9.7886	34 $^3P_2$ **Se** Selenium 78.971 [Ar]3d^{10}4s^{2}4p^4 9.7524	35 $^2P^\circ_{3/2}$ **Br** Bromine 79.904* [Ar]3d^{10}4s^{2}4p^5 11.8138	36 $^1S_0$ **Kr** Krypton 83.798 [Ar]3d^{10}4s^{2}4p^6 13.9996
5	37 $^2S_{1/2}$ **Rb** Rubidium 85.4678 [Kr]5s 4.1771	38 $^1S_0$ **Sr** Strontium 87.62 [Kr]5s^2 5.6949	39 $^2D_{3/2}$ **Y** Yttrium 88.90584 [Kr]4d5s^2 6.2173	40 $^3F_2$ **Zr** Zirconium 91.224 [Kr]4d^{2}5s^2 6.6339	41 $^6D_{1/2}$ **Nb** Niobium 92.90637 [Kr]4d^{4}5s 6.7589	42 $^7S_3$ **Mo** Molybdenum 95.95 [Kr]4d^{5}5s 7.0924	43 $^6S_{5/2}$ **Tc** Technetium (98) [Kr]4d^{5}5s^2 7.1194	44 $^5F_5$ **Ru** Ruthenium 101.07 [Kr]4d^{7}5s 7.3605	45 $^4F_{9/2}$ **Rh** Rhodium 102.90550 [Kr]4d^{8}5s 7.4589	46 $^1S_0$ **Pd** Palladium 106.42 [Kr]4d^{10} 8.3369	47 $^2S_{1/2}$ **Ag** Silver 107.8682 [Kr]4d^{10}5s 7.5762	48 $^1S_0$ **Cd** Cadmium 112.414 [Kr]4d^{10}5s^2 8.9938	49 $^2P^\circ_{1/2}$ **In** Indium 114.818 [Kr]4d^{10}5s^{2}5p 5.7864	50 $^3P_0$ **Sn** Tin 118.710 [Kr]4d^{10}5s^{2}5p^2 7.3439	51 $^4S^\circ_{3/2}$ **Sb** Antimony 121.760 [Kr]4d^{10}5s^{2}5p^3 8.6084	52 $^3P_2$ **Te** Tellurium 127.60 [Kr]4d^{10}5s^{2}5p^4 9.0097	53 $^2P^\circ_{3/2}$ **I** Iodine 126.90447 [Kr]4d^{10}5s^{2}5p^5 10.4513	54 $^1S_0$ **Xe** Xenon 131.293 [Kr]4d^{10}5s^{2}5p^6 12.1298
6	55 $^2S_{1/2}$ **Cs** Cesium 132.9054520 [Xe]6s 3.8939	56 $^1S_0$ **Ba** Barium 137.327 [Xe]6s^2 5.2117		72 $^3F_2$ **Hf** Hafnium 178.49 [Xe]4f^{14}5d^{2}6s^2 6.8251	73 $^4F_{3/2}$ **Ta** Tantalum 180.94788 [Xe]4f^{14}5d^{3}6s^2 7.5496	74 $^5D_0$ **W** Tungsten 183.84 [Xe]4f^{14}5d^{4}6s^2 7.8640	75 $^6S_{5/2}$ **Re** Rhenium 186.207 [Xe]4f^{14}5d^{5}6s^2 7.8335	76 $^5D_4$ **Os** Osmium 190.23 [Xe]4f^{14}5d^{6}6s^2 8.4382	77 $^4F_{9/2}$ **Ir** Iridium 192.217 [Xe]4f^{14}5d^{7}6s^2 8.9670	78 $^3D_3$ **Pt** Platinum 195.084 [Xe]4f^{14}5d^{9}6s 8.9588	79 $^2S_{1/2}$ **Au** Gold 196.966569 [Xe]4f^{14}5d^{10}6s 9.2256	80 $^1S_0$ **Hg** Mercury 200.592 [Xe]4f^{14}5d^{10}6s^2 10.4375	81 $^2P^\circ_{1/2}$ **Tl** Thallium 204.38* [Hg]6p 6.1083	82 $^3P_0$ **Pb** Lead 207.2 [Hg]6p^2 7.4167	83 $^4S^\circ_{3/2}$ **Bi** Bismuth 208.98040 [Hg]6p^3 7.2855	84 $^3P_2$ **Po** Polonium (209) [Hg]6p^4 8.414	85 $^2P^\circ_{3/2}$ **At** Astatine (210) [Hg]6p^5 9.31751	86 $^1S_0$ **Rn** Radon (222) [Hg]6p^6 10.7485
7	87 $^2S_{1/2}$ **Fr** Francium (223) [Rn]7s 4.0727	88 $^1S_0$ **Ra** Radium (226) [Rn]7s^2 5.2784		104 $^3F_2$ **Rf** Rutherfordium (267) [Rn]5f^{14}6d^{2}7s^2 6.01	105 $^4F_{3/2}$ **Db** Dubnium (268) [Rn]5f^{14}6d^{3}7s^2 6.8	106 **Sg** Seaborgium (271) [Rn]5f^{14}6d^{4}7s^2 7.8	107 **Bh** Bohrium (272) [Rn]5f^{14}6d^{5}7s^2 7.7	108 **Hs** Hassium (270) [Rn]5f^{14}6d^{6}7s^2 7.6	109 **Mt** Meitnerium (276)	110 **Ds** Darmstadtium (281)	111 **Rg** Roentgenium (280)	112 **Cn** Copernicium (285)	113 **Uut** Ununtrium (284)	114 **Fl** Flerovium (289)	115 **Uup** Ununpentium (288)	116 **Lv** Livermorium (293)	117 **Uus** Ununseptium (294)	118 **Uuo** Ununoctium (294)

Lanthanides	57 $^2D_{3/2}$ **La** Lanthanum 138.90547 [Xe]5d6s^2 5.5769	58 $^1G^\circ_4$ **Ce** Cerium 140.116 [Xe]4f5d6s^2 5.5386	59 $^4I^\circ_{9/2}$ **Pr** Praseodymium 140.907 [Xe]4f^{3}6s^2 5.473	60 $^5I_4$ **Nd** Neodymium 144.242 [Xe]4f^{4}6s^2 5.5250	61 $^6H^\circ_{5/2}$ **Pm** Promethium (145) [Xe]4f^{5}6s^2 5.582	62 $^7F_0$ **Sm** Samarium 150.36 [Xe]4f^{6}6s^2 5.6437	63 $^8S^\circ_{7/2}$ **Eu** Europium 151.964 [Xe]4f^{7}6s^2 5.6704	64 $^9D^\circ_2$ **Gd** Gadolinium 157.25 [Xe]4f^{7}5d6s^2 6.1498	65 $^6H^\circ_{15/2}$ **Tb** Terbium 158.92535 [Xe]4f^{9}6s^2 5.8638	66 $^5I_8$ **Dy** Dysprosium 162.500 [Xe]4f^{10}6s^2 5.9391	67 $^4I^\circ_{15/2}$ **Ho** Holmium 164.93033 [Xe]4f^{11}6s^2 6.0215	68 $^3H_6$ **Er** Erbium 167.259 [Xe]4f^{12}6s^2 6.1077	69 $^2F^\circ_{7/2}$ **Tm** Thulium 168.93422 [Xe]4f^{13}6s^2 6.1843	70 $^1S_0$ **Yb** Ytterbium 173.054 [Xe]4f^{14}6s^2 6.2542	71 $^2D_{3/2}$ **Lu** Lutetium 174.9668 [Xe]4f^{14}5d6s^2 5.4259
Actinides	89 $^2D_{3/2}$ **Ac** Actinium (227) [Rn]6d7s^2 5.3802	90 $^3F_2$ **Th** Thorium 232.0377 [Rn]6d^{2}7s^2 6.3067	91 $^4K_{11/2}$ **Pa** Protactinium 231.03588 [Rn]5f^{2}6d7s^2 5.89	92 $^5L^\circ_6$ **U** Uranium 238.02891 [Rn]5f^{3}6d7s^2 6.1941	93 $^6L_{11/2}$ **Np** Neptunium (237) [Rn]5f^{4}6d7s^2 6.2655	94 $^7F_0$ **Pu** Plutonium (244) [Rn]5f^{6}7s^2 6.0258	95 $^8S^\circ_{7/2}$ **Am** Americium (243) [Rn]5f^{7}7s^2 5.9738	96 $^9D^\circ_2$ **Cm** Curium (247) [Rn]5f^{7}6d7s^2 5.9914	97 $^6H^\circ_{15/2}$ **Bk** Berkelium (247) [Rn]5f^{9}7s^2 6.1978	98 $^5I_8$ **Cf** Californium (251) [Rn]5f^{10}7s^2 6.2817	99 $^4I^\circ_{15/2}$ **Es** Einsteinium (252) [Rn]5f^{11}7s^2 6.3676	100 $^3H_6$ **Fm** Fermium (257) [Rn]5f^{12}7s^2 6.50	101 $^2F^\circ_{7/2}$ **Md** Mendelevium (258) [Rn]5f^{13}7s^2 6.58	102 $^1S_0$ **No** Nobelium (259) [Rn]5f^{14}7s^2 6.65	103 $^2P^\circ_{1/2}$ **Lr** Lawrencium (262) [Rn]5f^{14}7s^{2}7p 4.90

Atomic Number	58
Ground-state Level	$^1G^\circ_4$
Symbol	**Ce**
Name	Cerium
Standard Atomic Weight†	140.116
Ground-state Configuration	[Xe]4f5d6s^2
Ionization Energy (eV)	5.5386

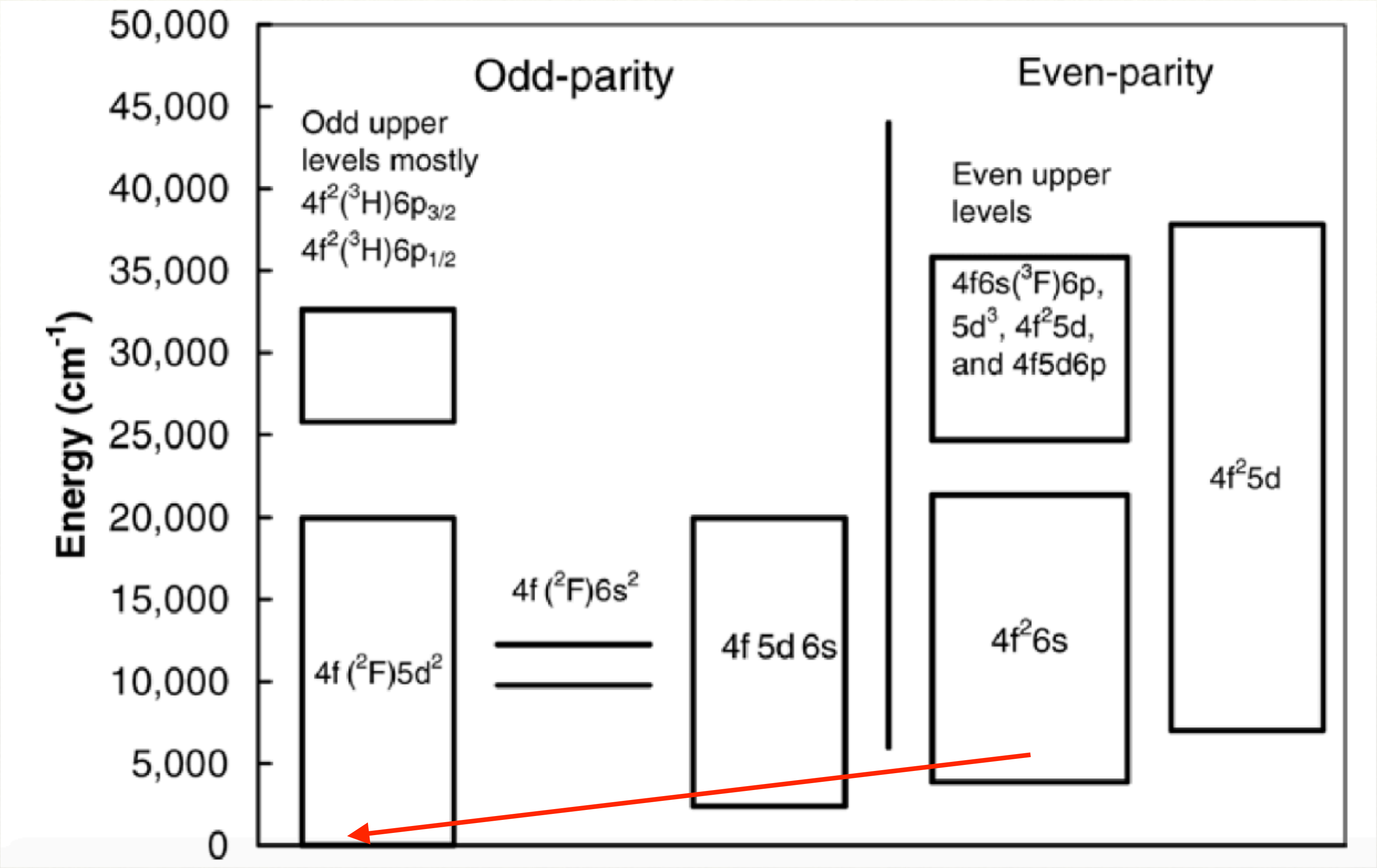
†Based upon ^{12}C. () indicates the mass number of the longest-lived isotope.

*IUPAC conventional atomic weights; standard atomic weights for these elements are expressed in intervals; see iupac.org for an explanation and values.

For a description of the data, visit physics.nist.gov/data

NIST SP 966 (September 2014)

Ce II

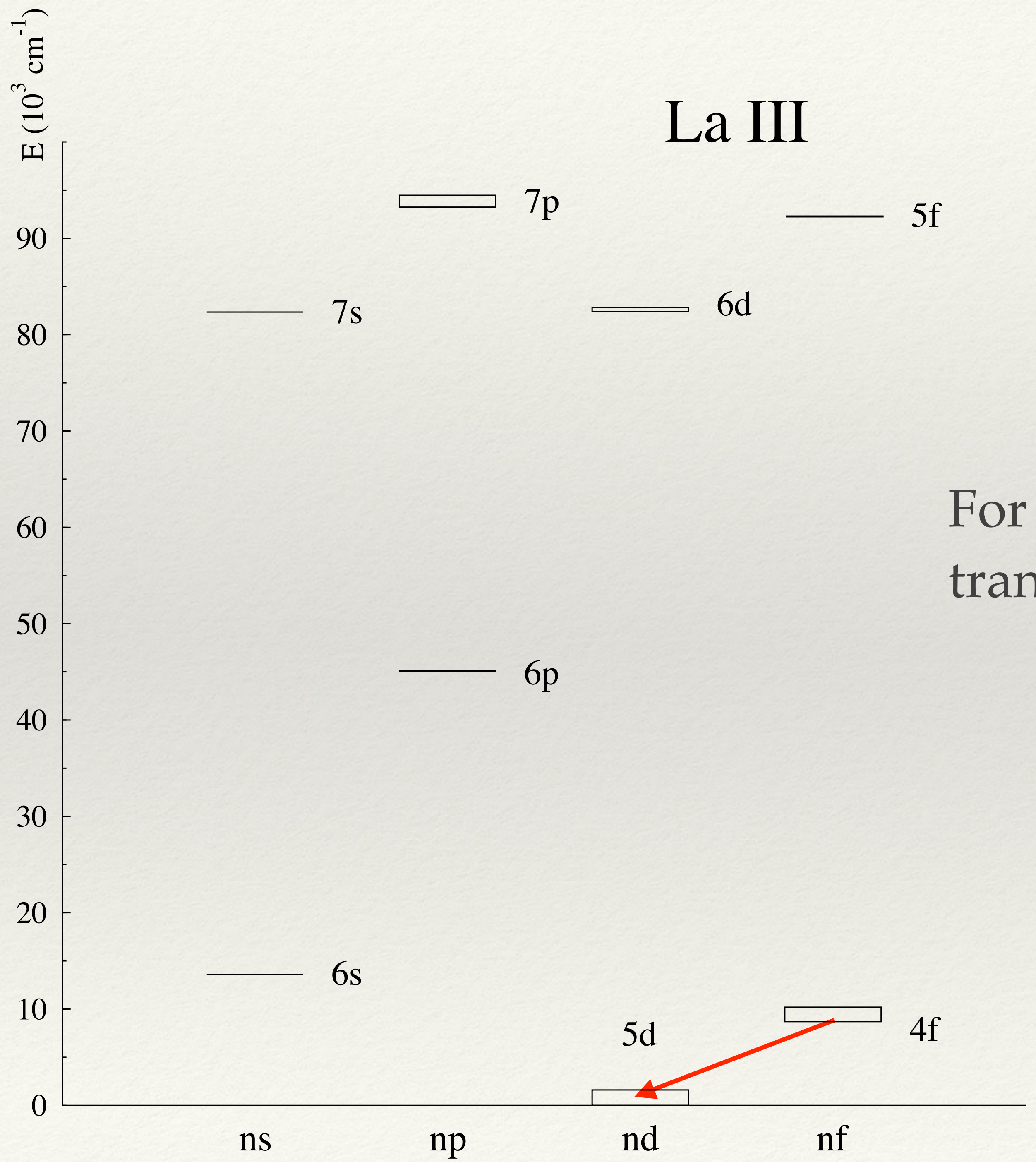


The open f-shell gives rise to the many levels and transitions. Resonance transitions in near-IR.

Lanthanides were earlier studied for applications to lighting applications, such as fluorescent tubes.

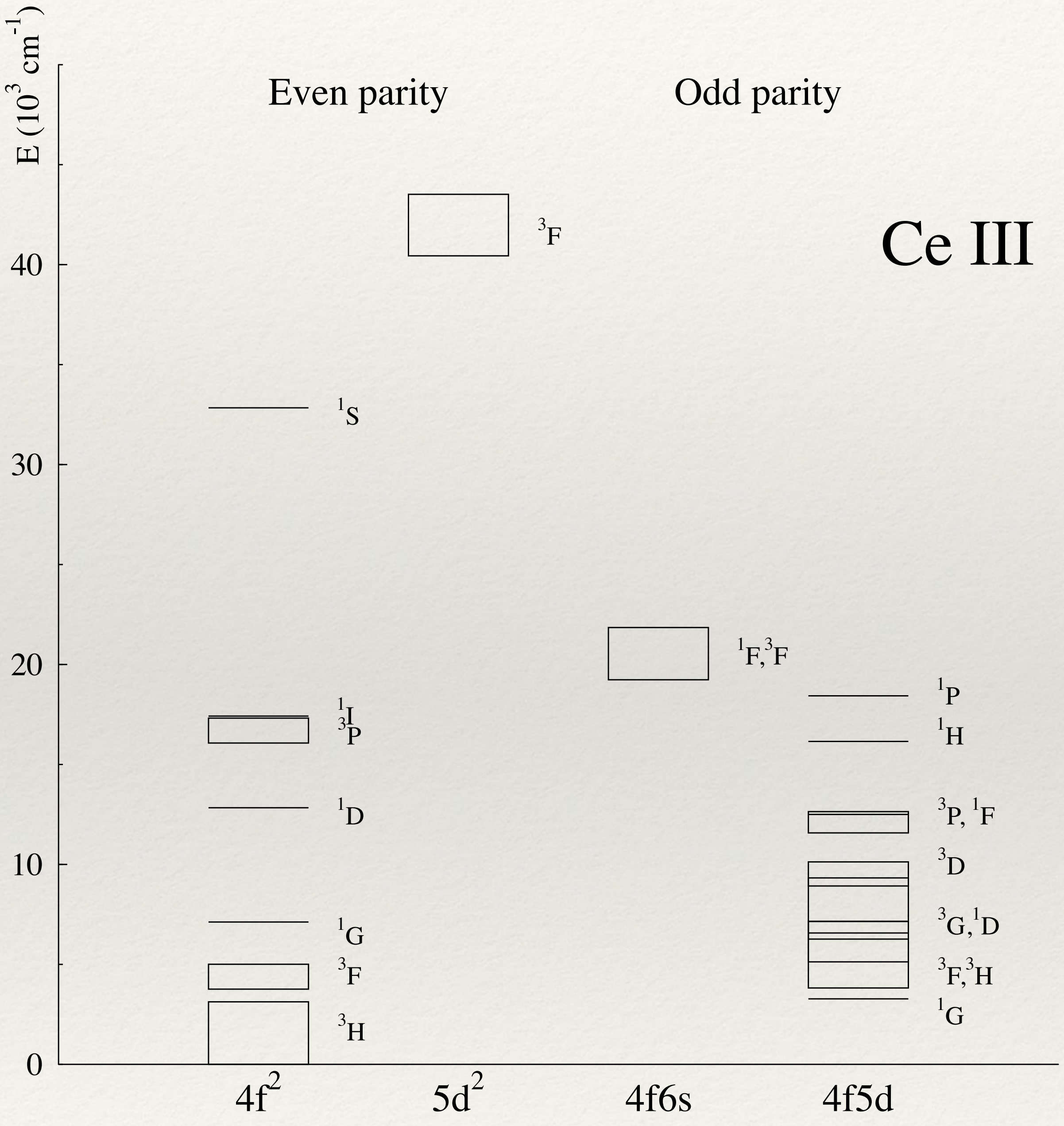
Lawler et al. (2001)

Lanthanum

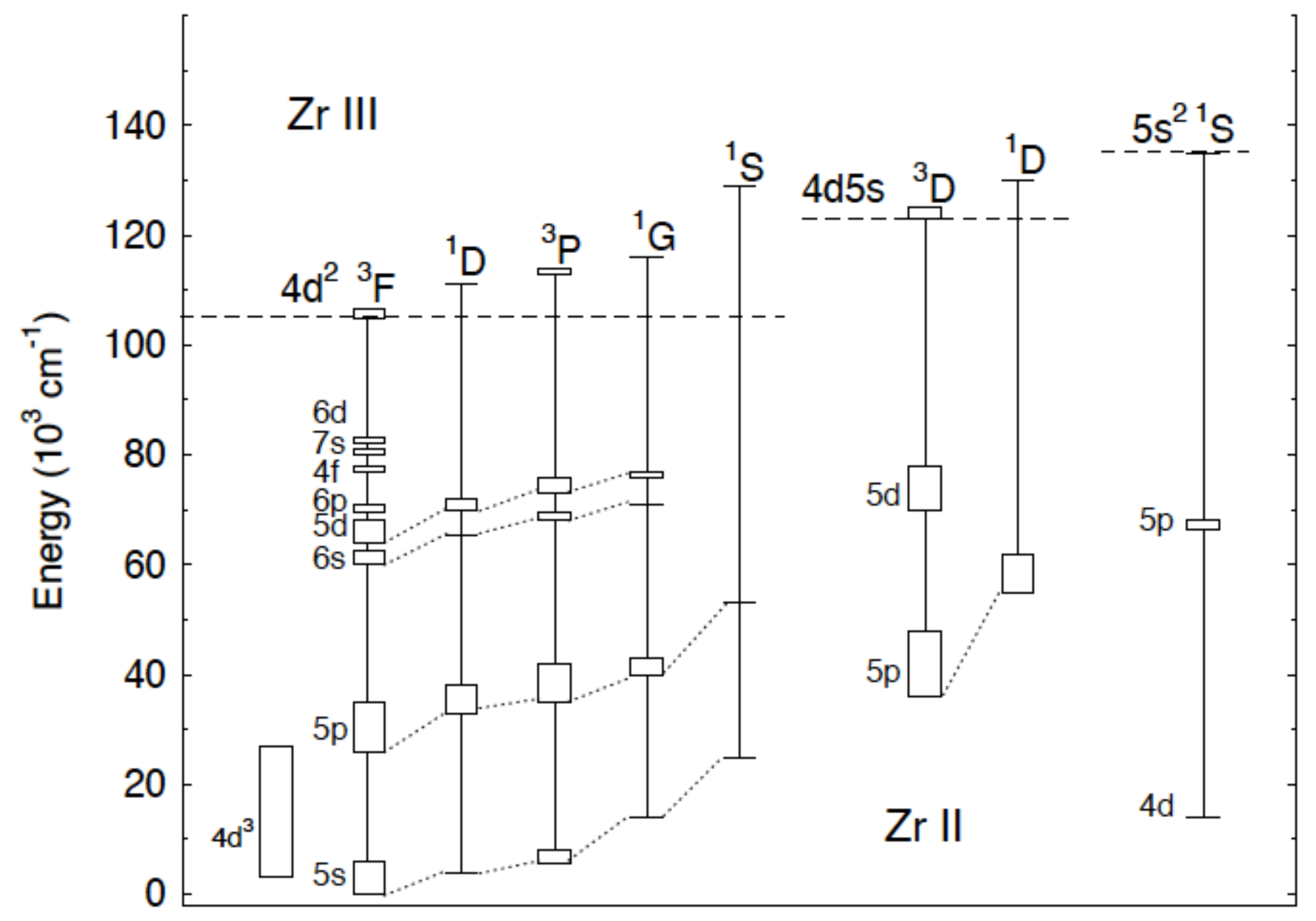


For many rare-earth elements, the near-IR transitions include the lowest excitation lines

Lowest levels of Ce III



Term analysis of Zr II



Burheim and Nilsson et al., in progress

Experimental transition rates (or f-values)

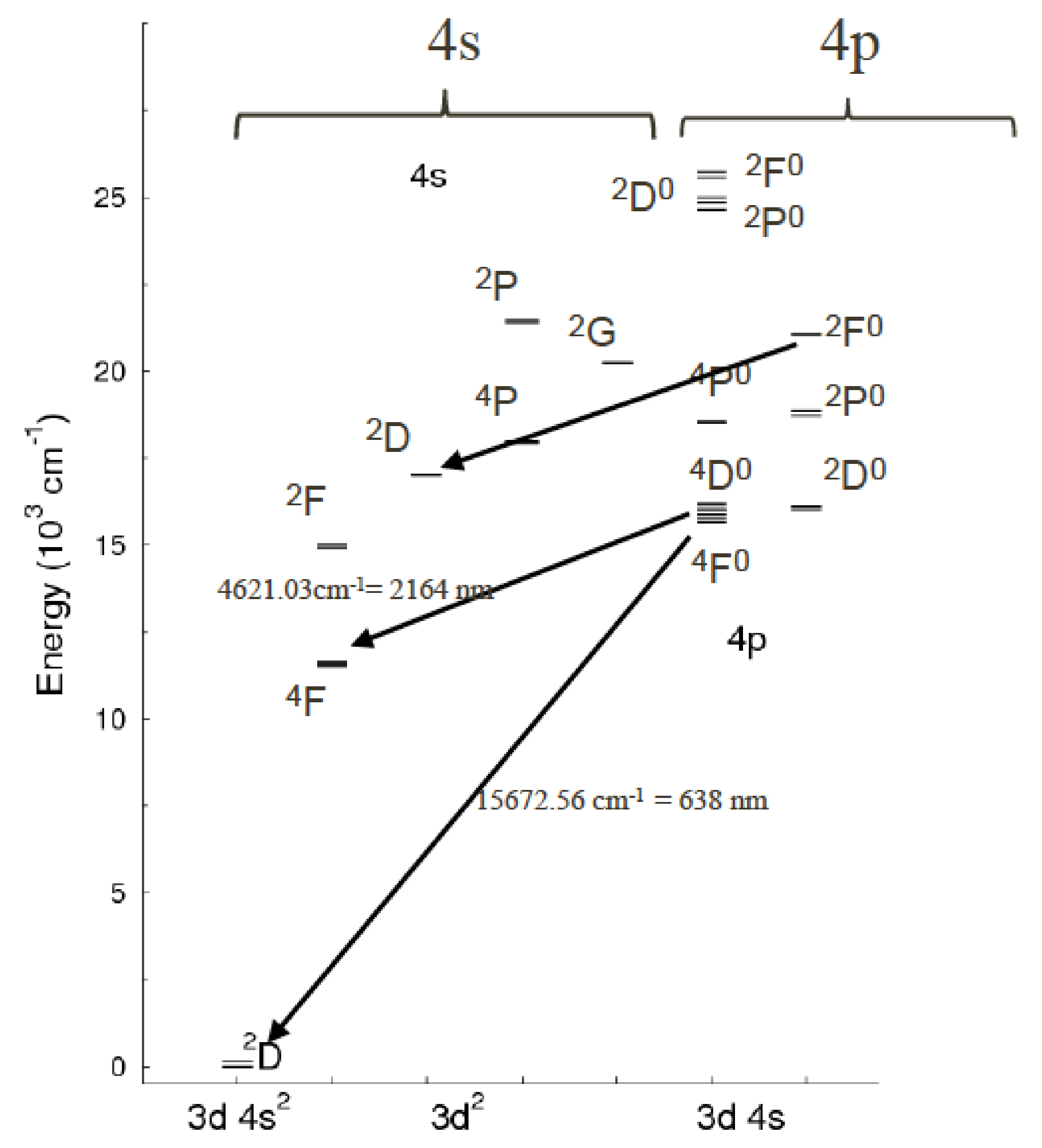
The transition rates A (or log gf-values) are derived from two *independently* measured quantities:

a) The relative emission line intensities from the lines from an common level

b) The radiative lifetime

$$A_{ul} = \frac{BF_{ul}}{\tau_u}$$

$$BF_{ul} = \frac{I_{ul}}{\sum_l I_{ul}}$$



Experimental transition rates (or f-values)

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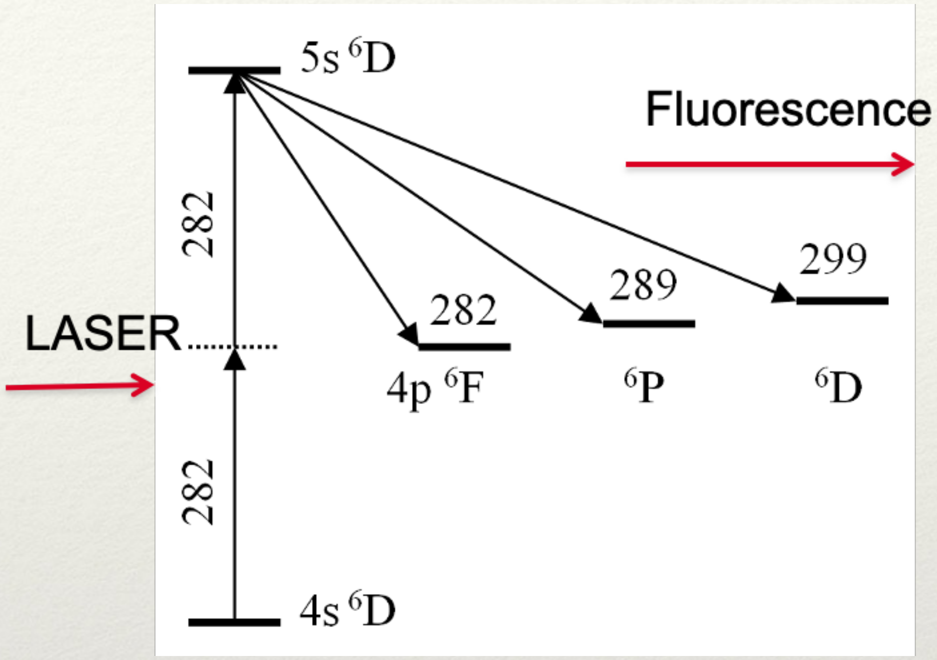
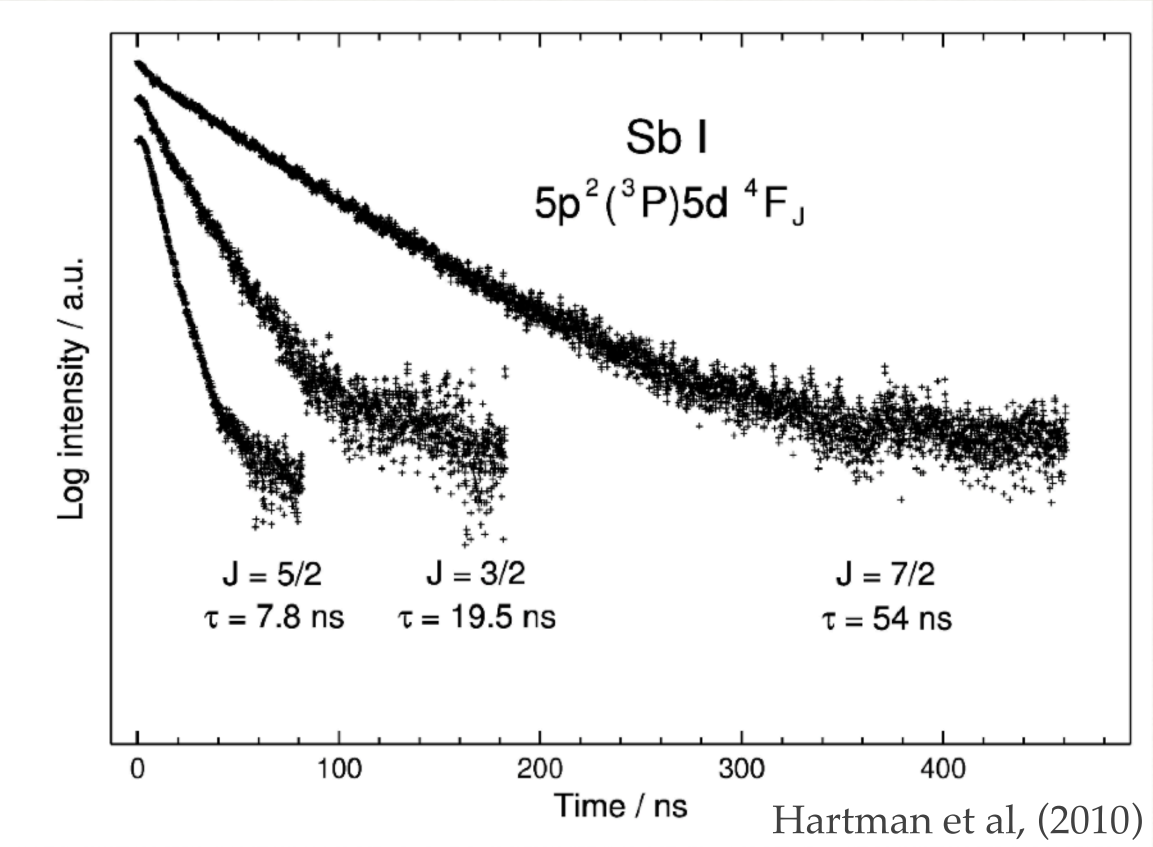
$$BF_{ul} = \frac{I_{ul}}{\sum_l I_{ul}}$$

Decay region	**Line spread**	**Lifetime**
Only optical	Narrow :)	1-20 ns :)
Optical+nIR	Broad :(	1-20 ns :)
Only nIR	Narrow :)	1-10 us :(

Lifetime measurements

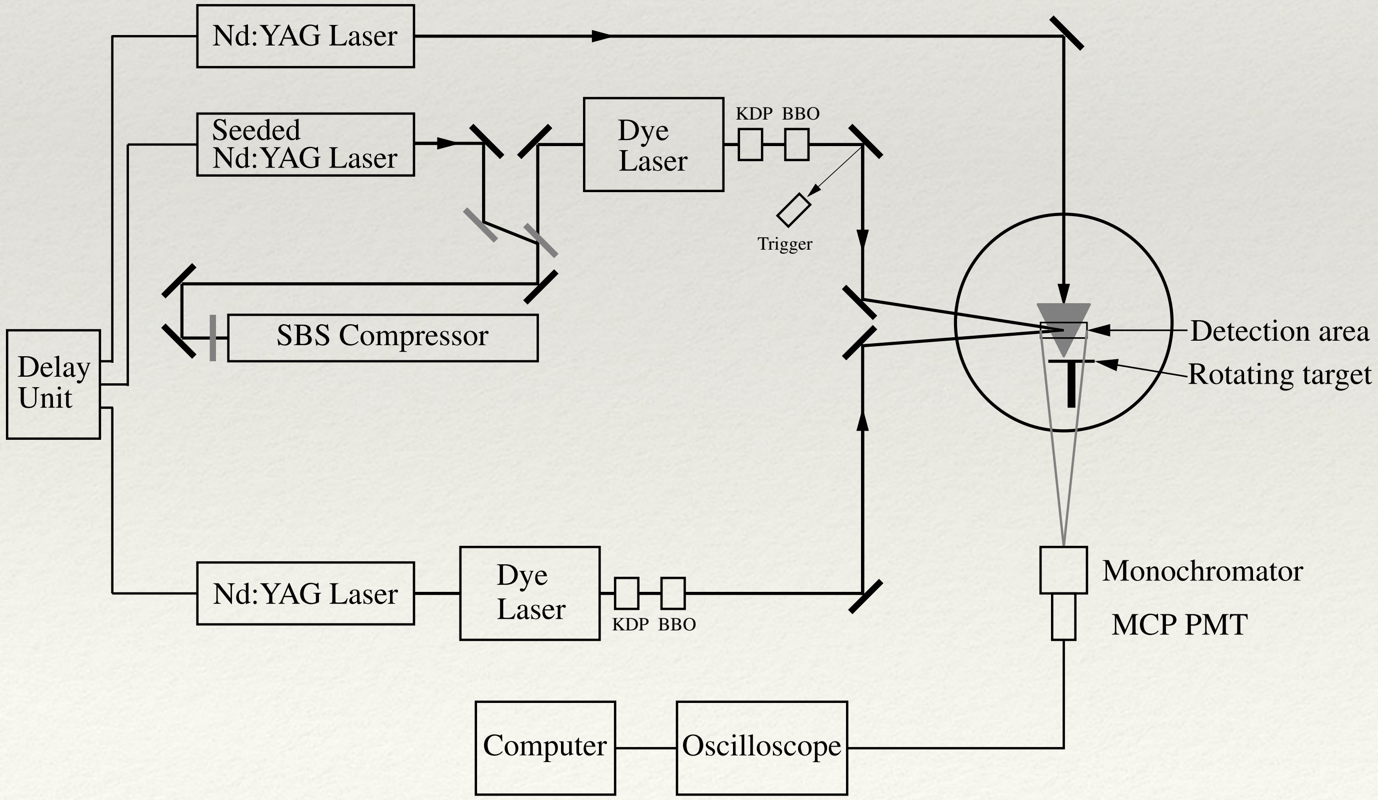


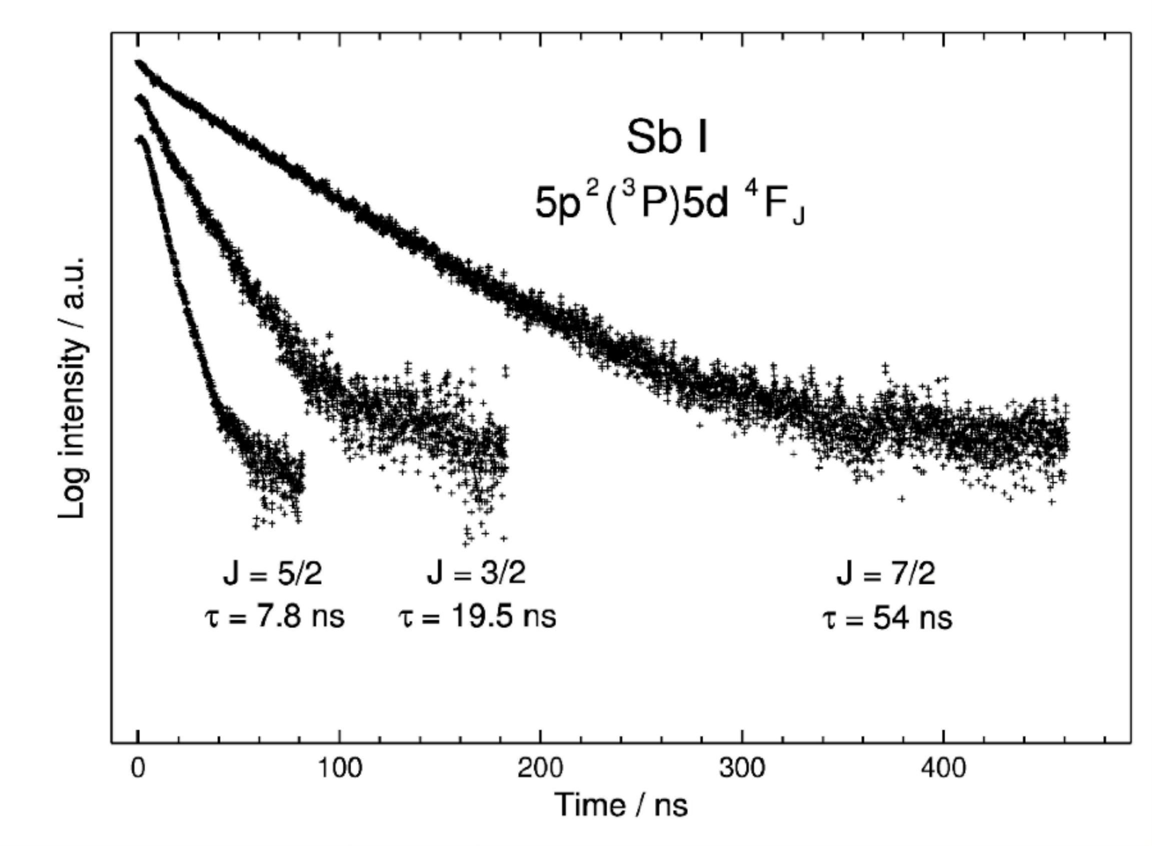


Hartman et al, (2010)

$$\tau_i = \frac{1}{\sum_j A_{ij}}$$

Laser induced plasma probed with short pulses (1ns)





Hartman et al, (2010)

Measurements of radiative lifetimes

- **University of Wisconsin (US)**

Measurements using one step excitation on ion beam

La I (2015), Sm I (2013), Nd I (2011), Gd I (2011), Er I (2010), Ce I (2009), Er II (2008), Nd II (2003), Eu I (2002), Tb II (2001)

- **Lund VUV laser lab (SE)**

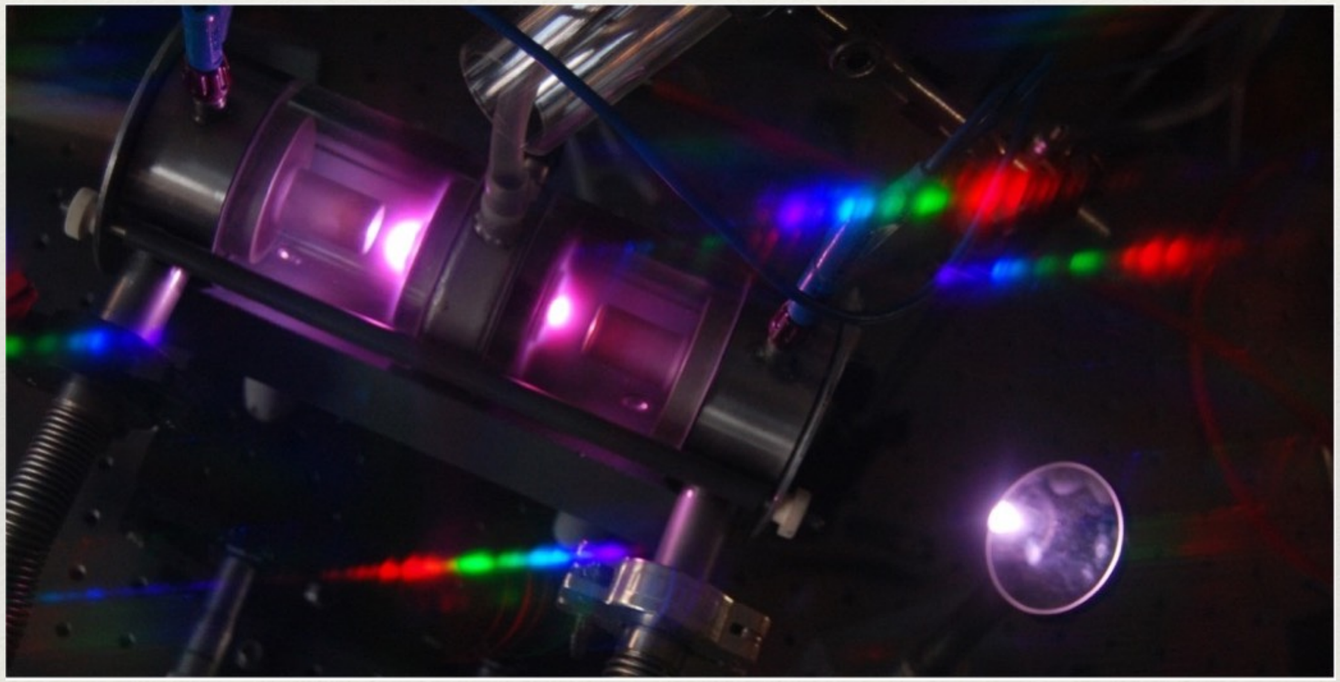
Laser induced fluorescence on laser produced plasma. One or two steps, can reach highly excited levels.

- **Jilin University, Changchun (CH)**

Experimental setup from the Lund VUV laser lab

Line Intensity measurements

Light source
Hollow cathode discharge lamp

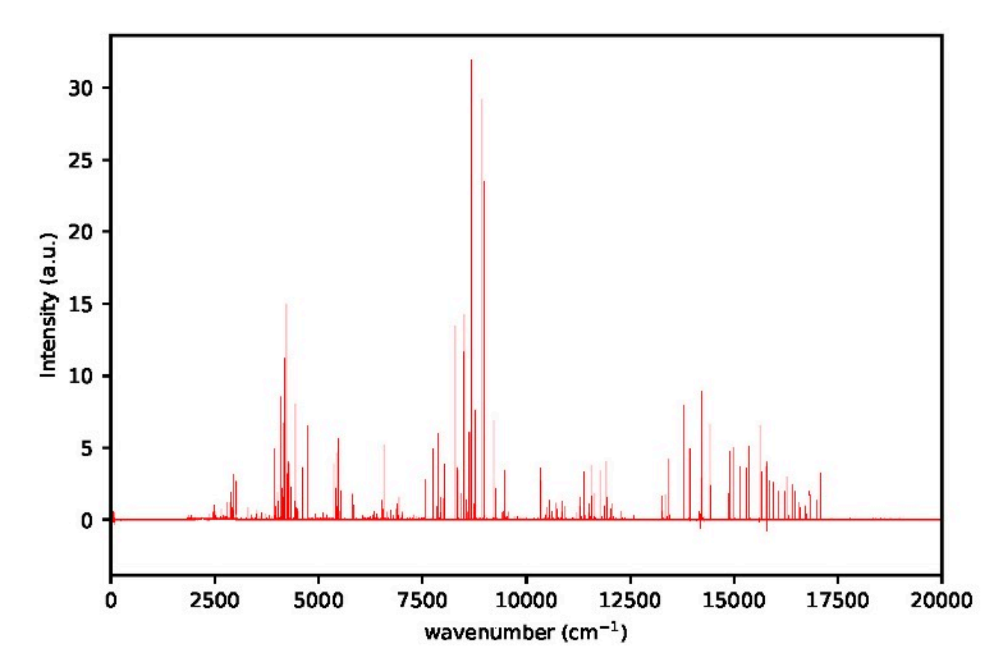


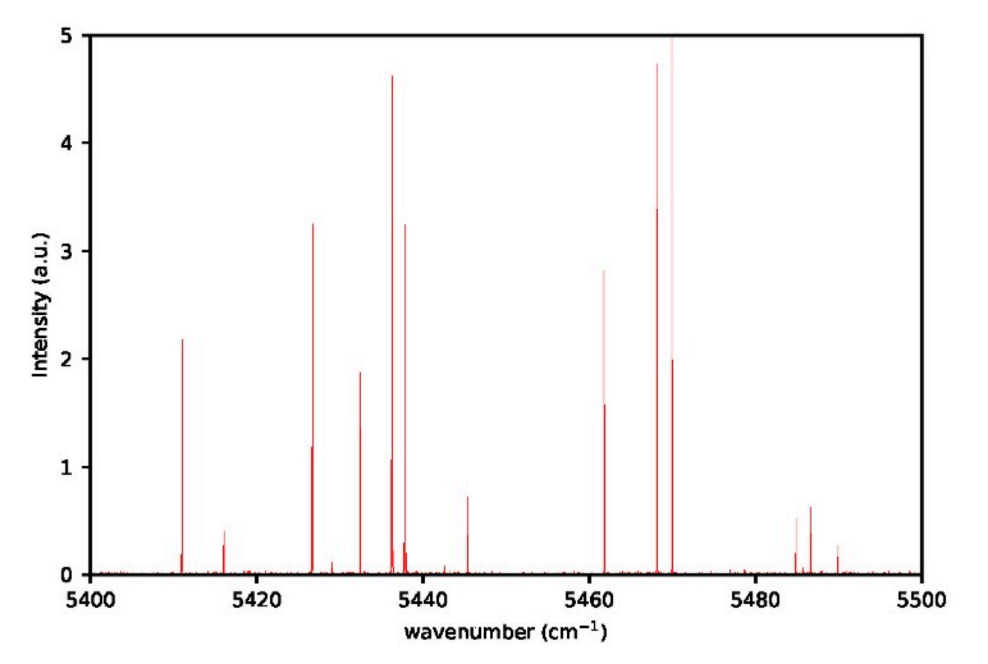
Plasma with neutral and singly ionized atoms

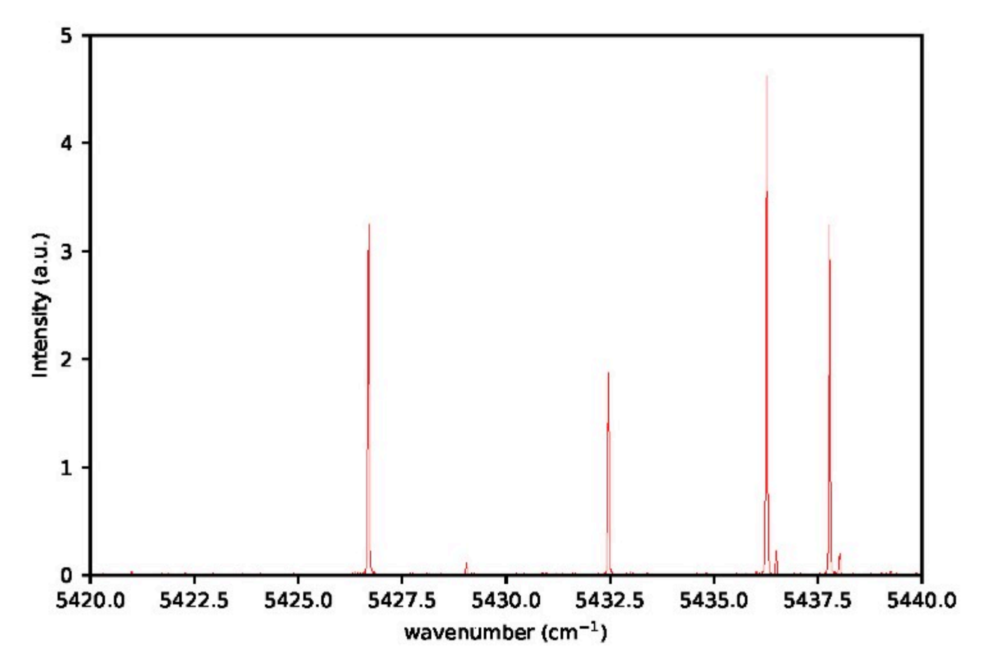
Detector
Fourier transform spectrometer

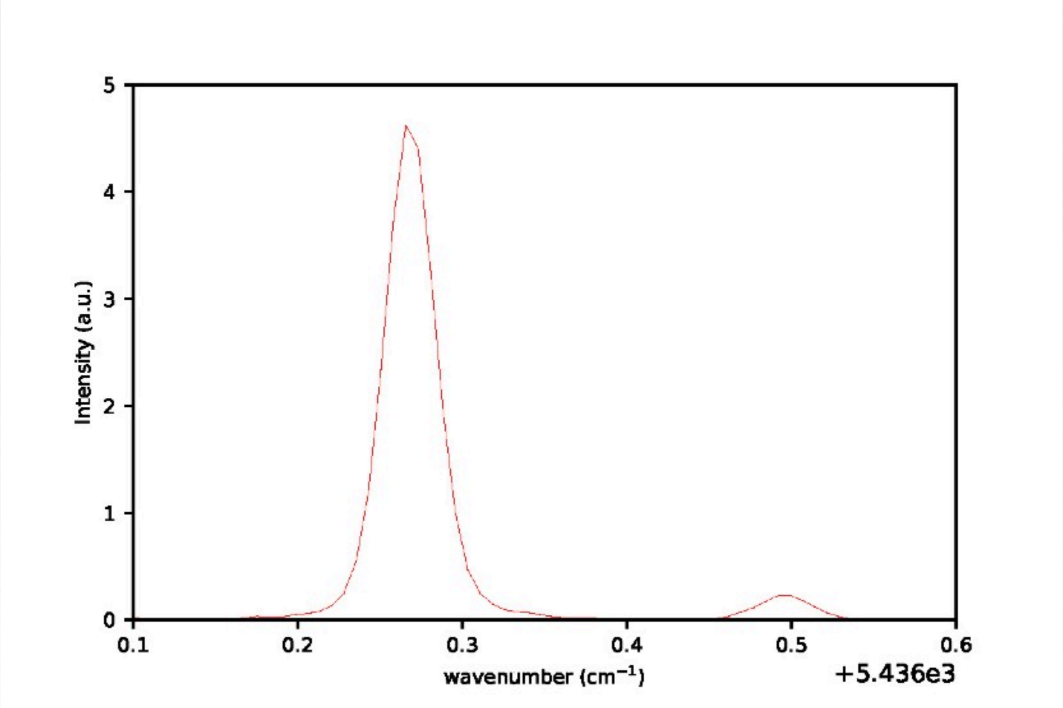
Near-IR and optical wavelength
Resolving power R=10^6
Wavelength calibration about 1:10^7

Emission spectrum of a Cerium discharge



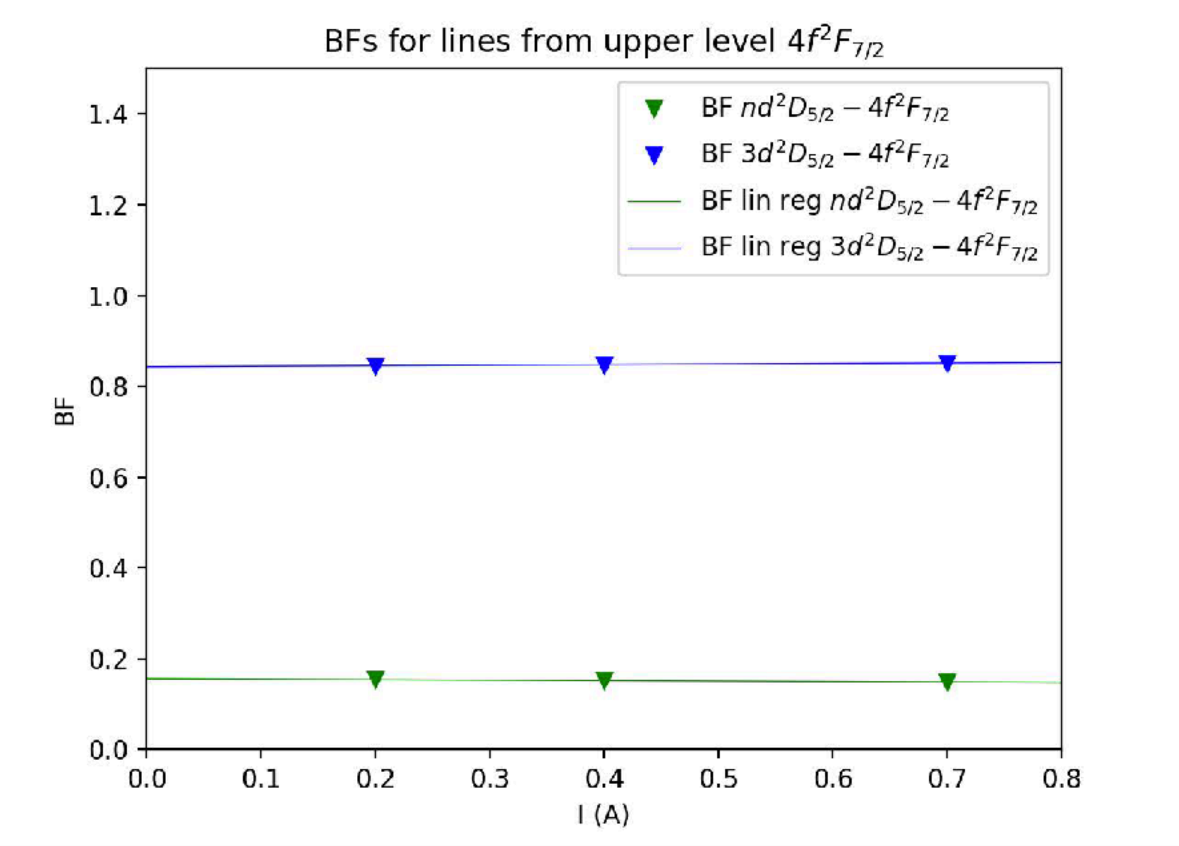


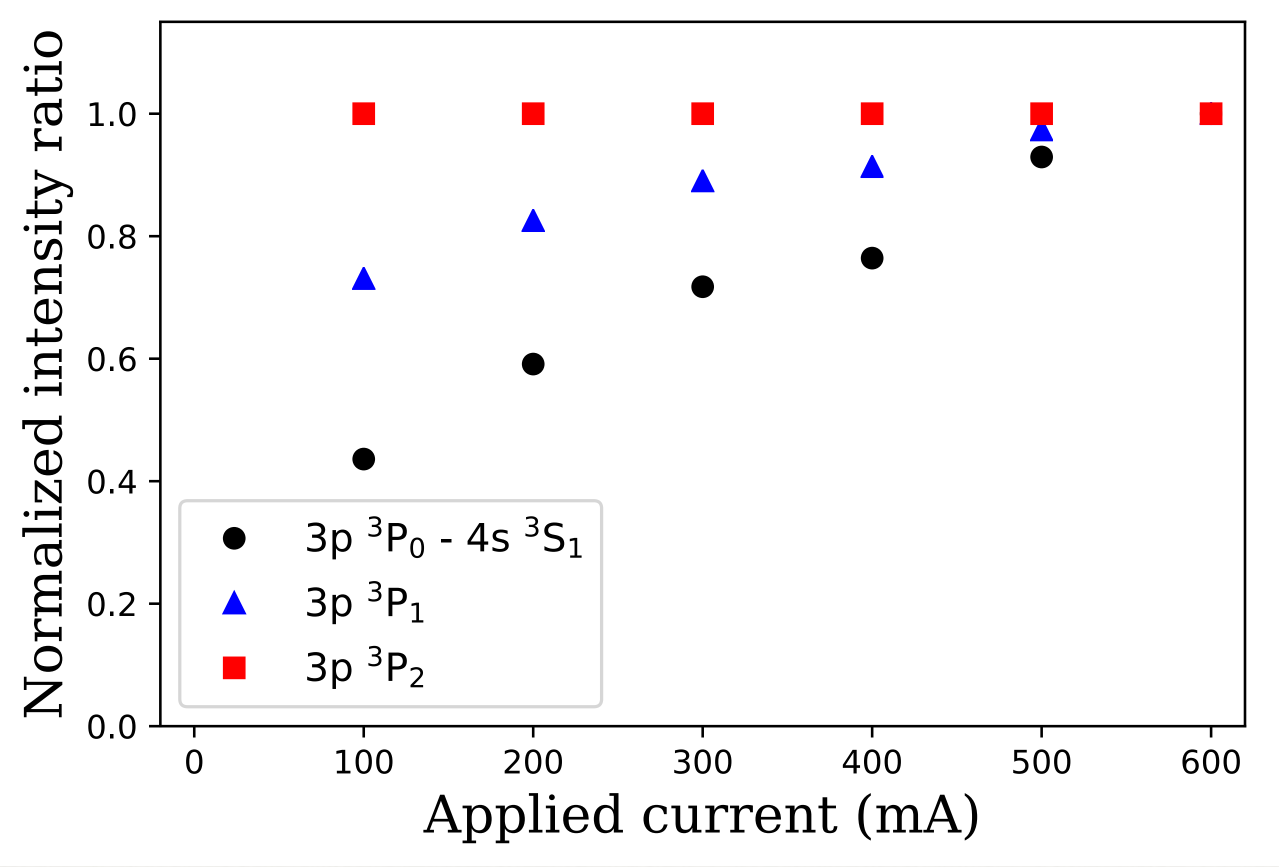




Measurements together with S.Caliskan, J.Grumer, M.Burheim, H.Nilsson

Radiative transfer effect in the discharge - self absorption





Combined approach for larger data sets

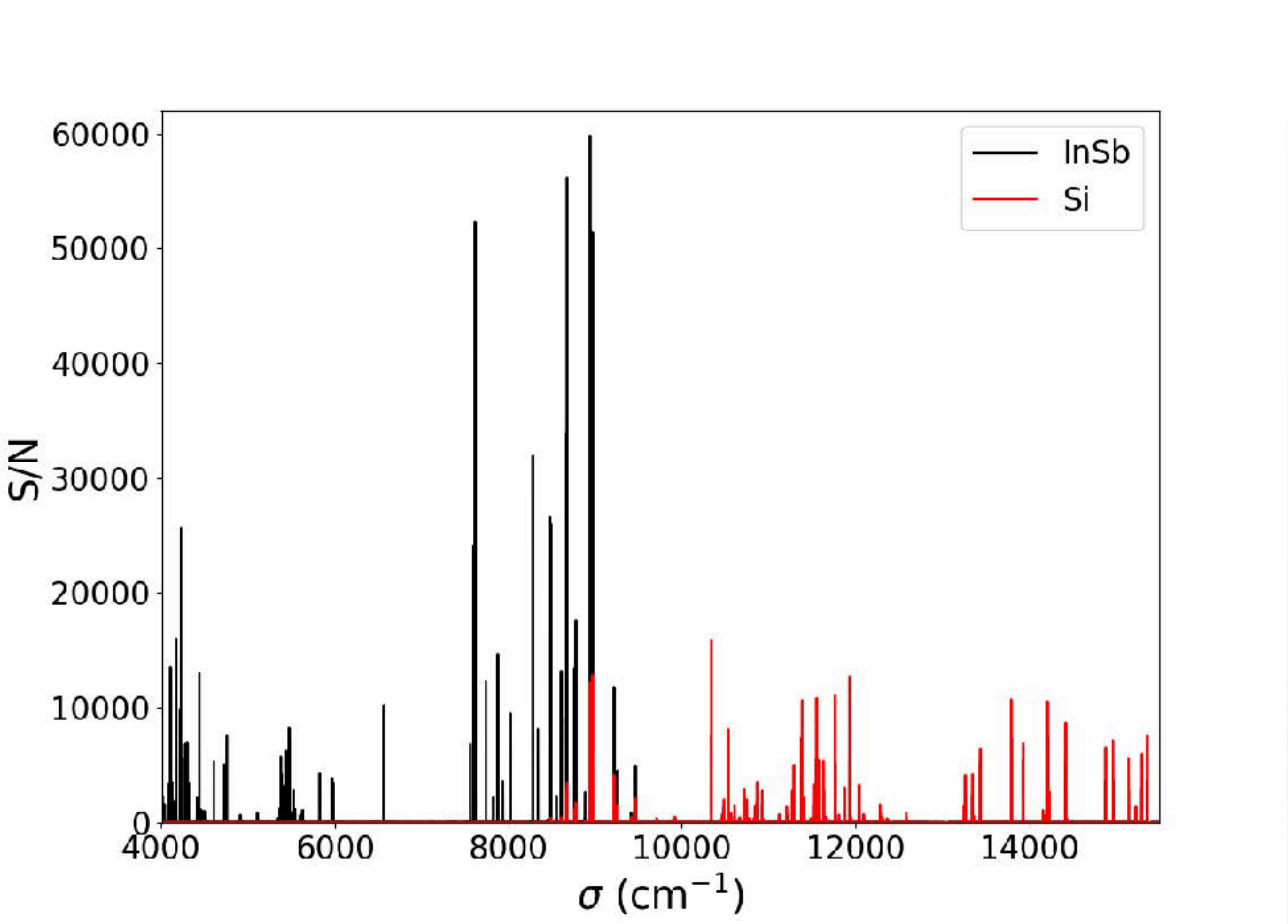
Approach for more complete sets of radiative data: Mg I, Al I, Si I/II:

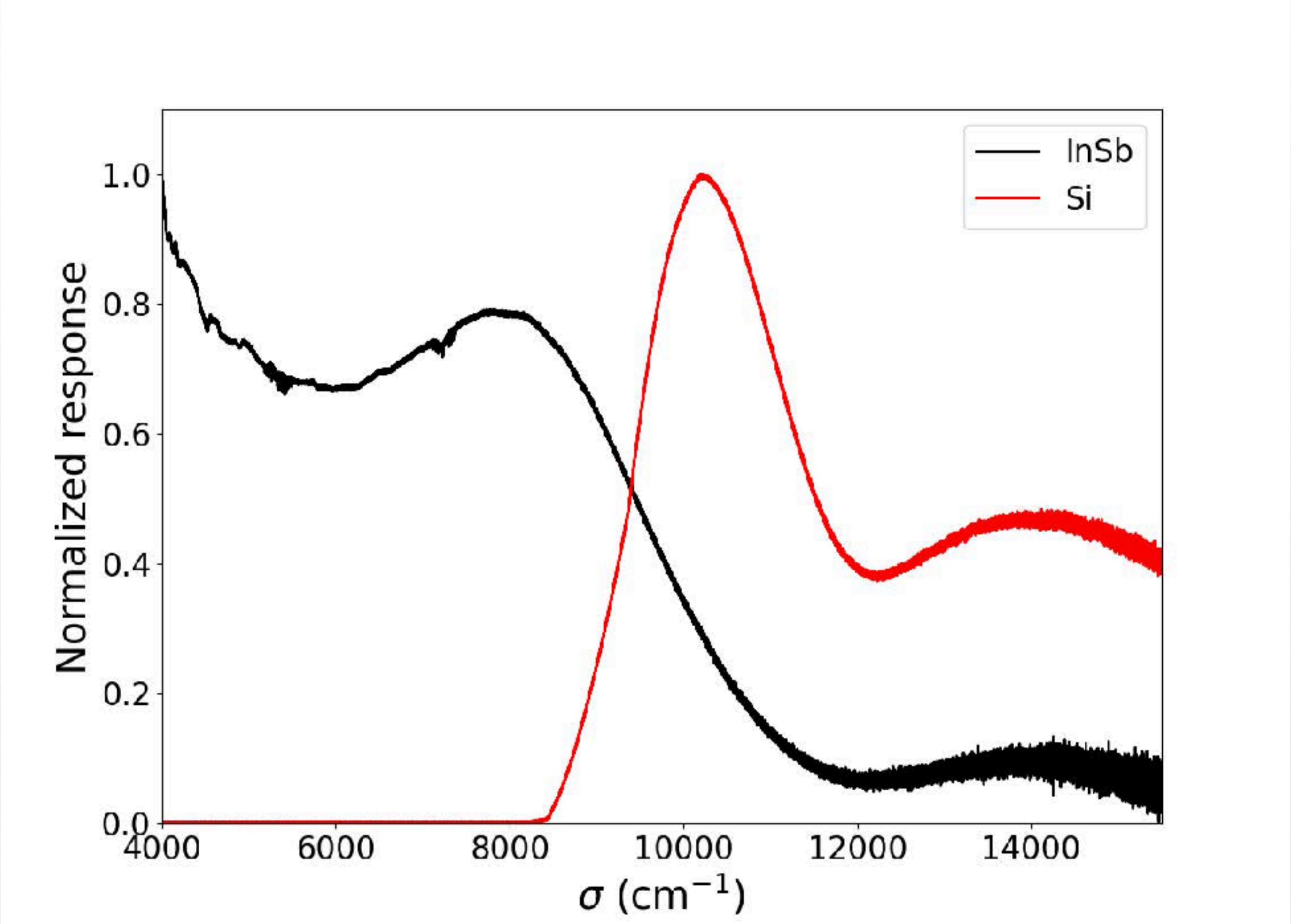
FTS measurements combined with lifetime data

ATSP2k or GRASP2k calculations for additional states and lifetimes

Stellar spectra for benchmarking, application and priorities
Linelists such as Gaia-ESO

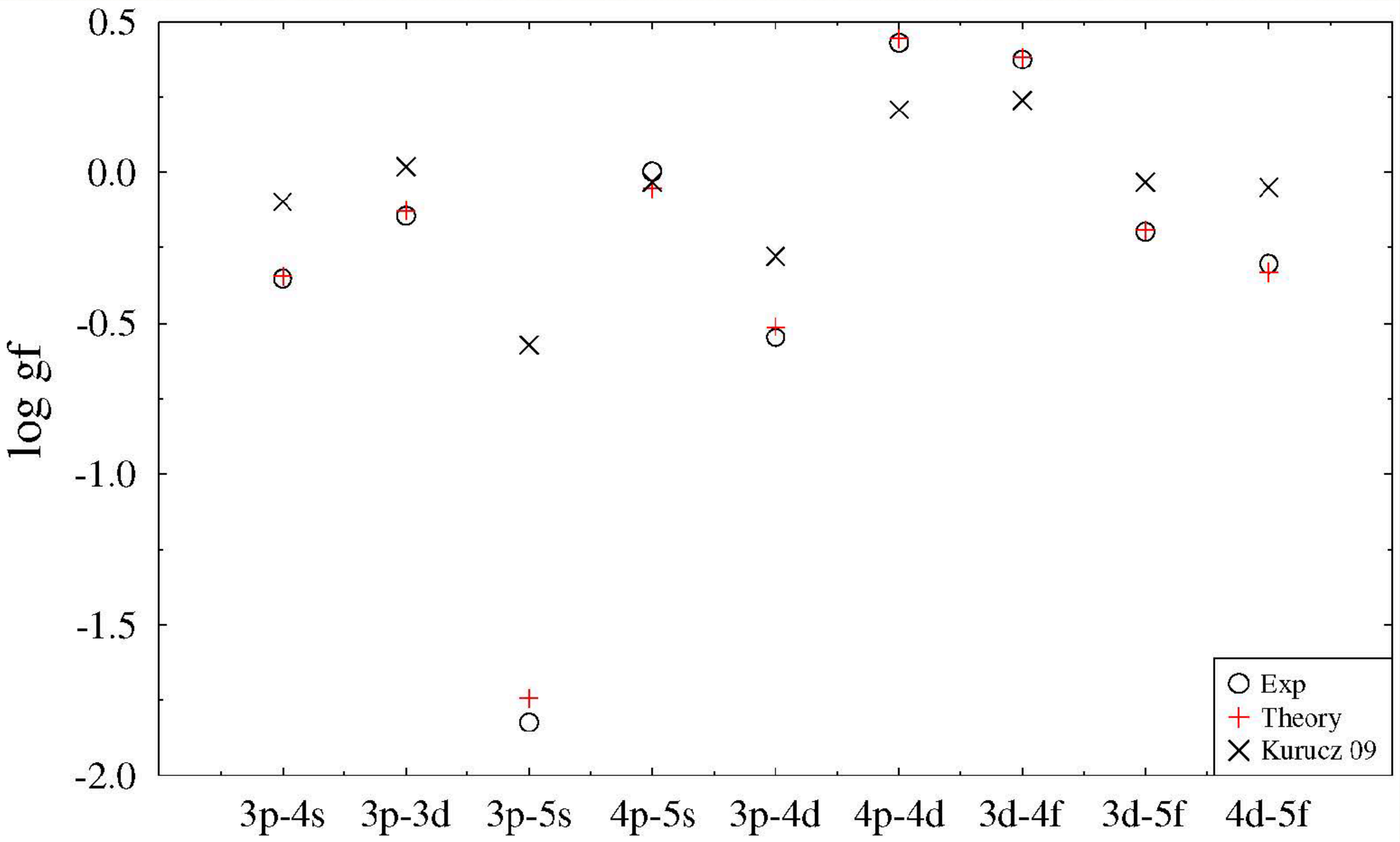
FTS spectrum of Aluminium





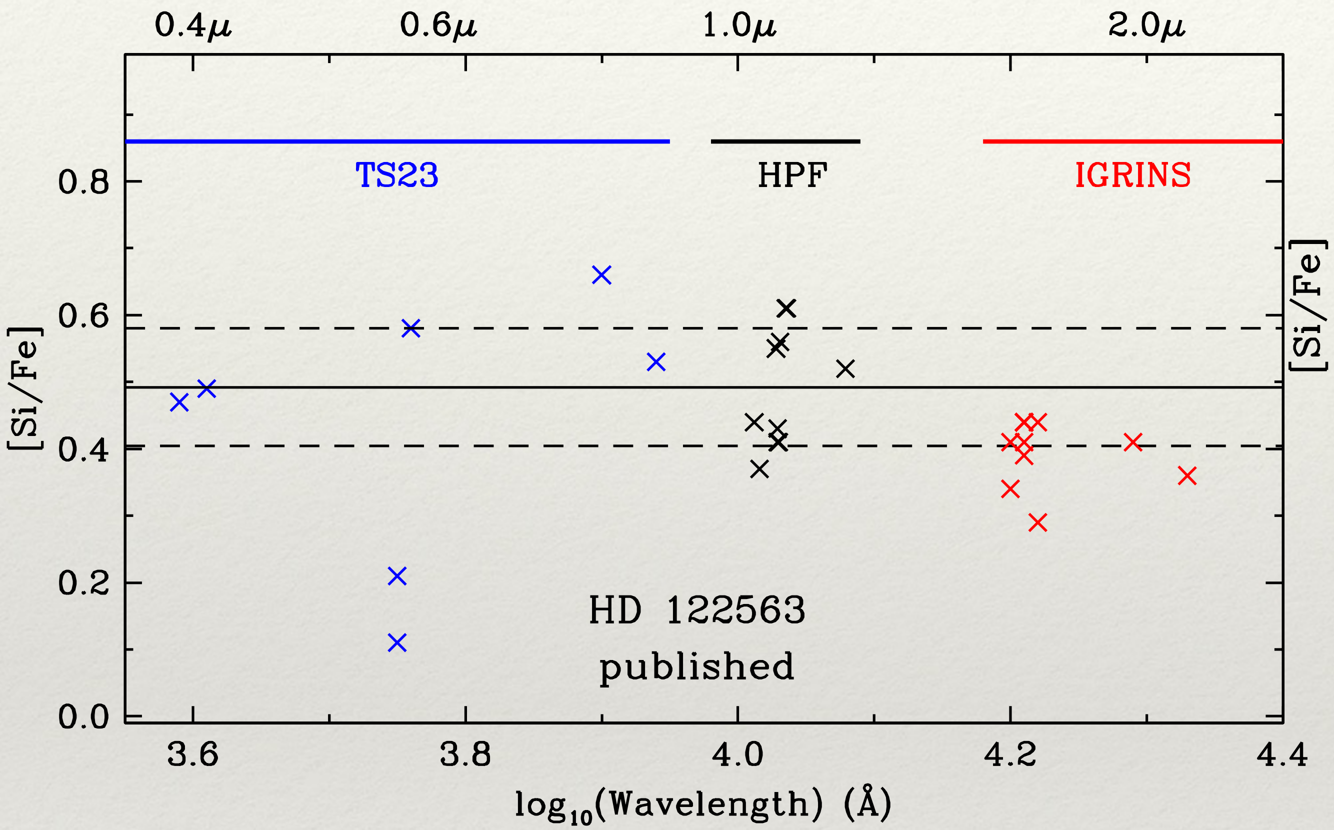
Burheim et al. A&A 672, A197, 2023)

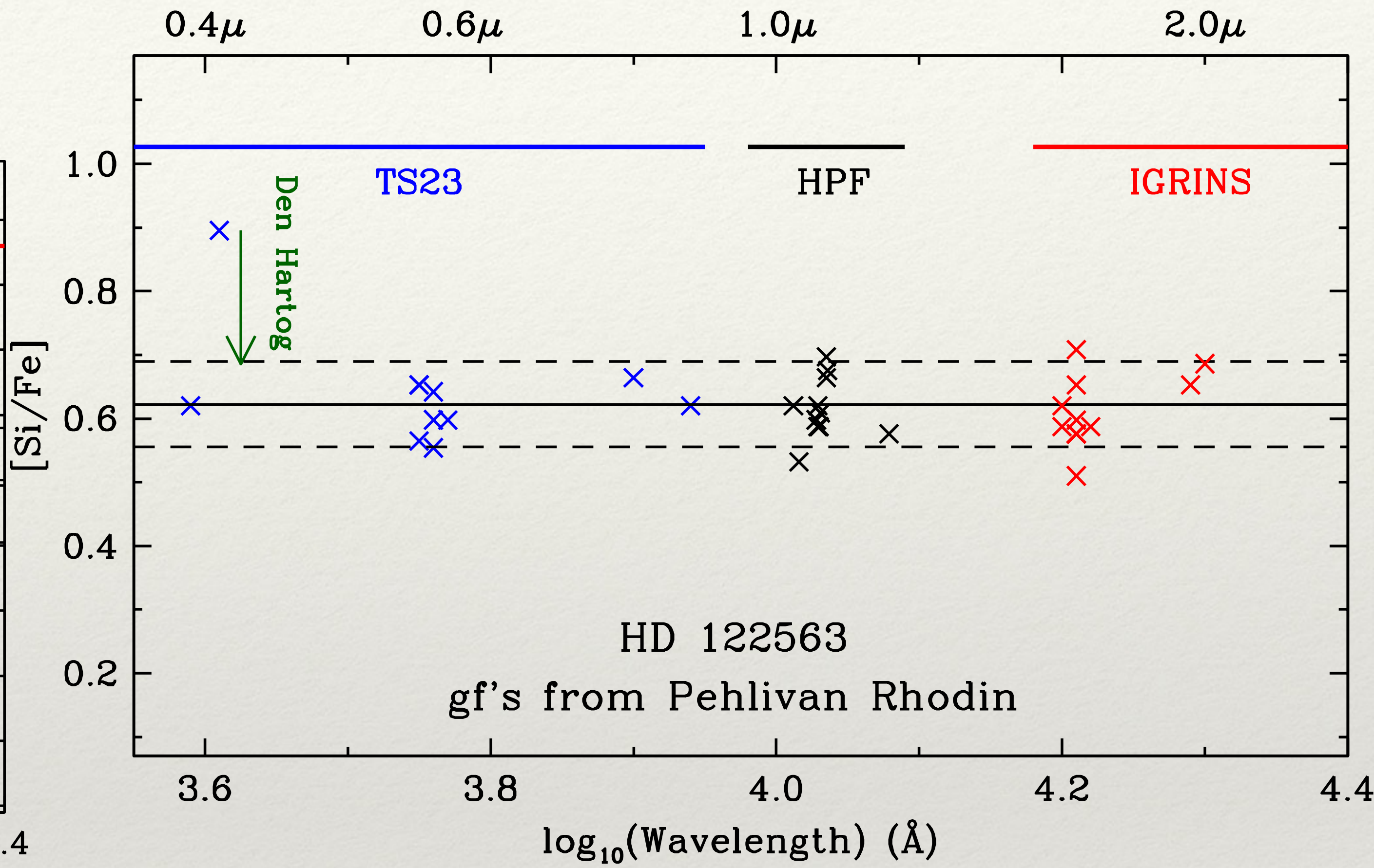
Results for Magnesium



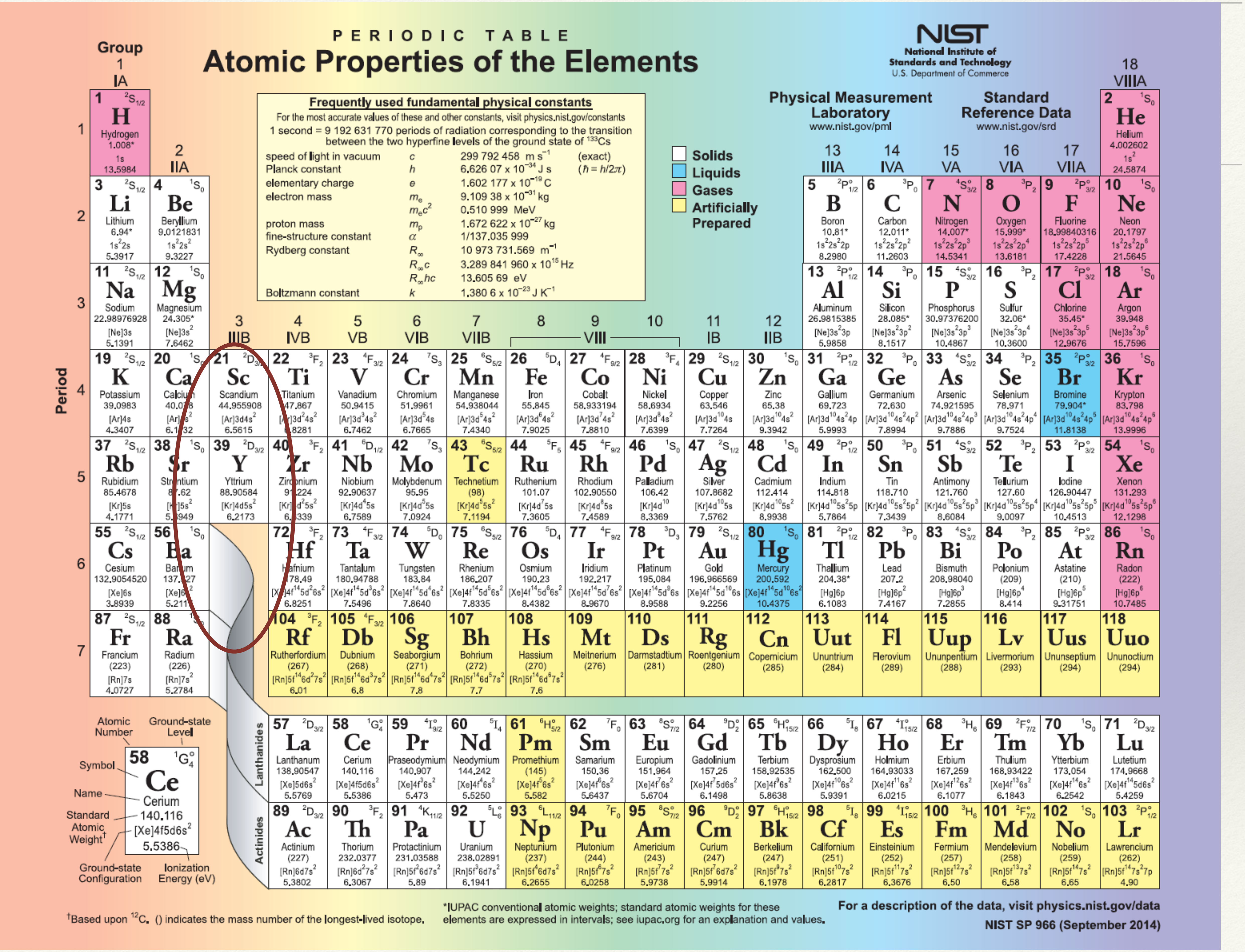
Mg I (Pehlivan Rhodin, et al., 2017)

Results Silicon





C. Sneden, private communication



PERIODIC TABLE

Atomic Properties of the Elements

NIST
National Institute of Standards and Technology
U.S. Department of Commerce

Physical Measurement Laboratory
www.nist.gov/pml

Standard Reference Data
www.nist.gov/srd

Frequently used fundamental physical constants

For the most accurate values of these and other constants, visit physics.nist.gov/constants

1 second = 9 192 631 770 periods of radiation corresponding to the transition between the two hyperfine levels of the ground state of ^{133}Cs

speed of light in vacuum	c	299 792 458 m s^{-1}	(exact)
Planck constant	h	$6.626\,07 \times 10^{-34}$ J s	($\hbar = h/2\pi$)
elementary charge	e	$1.602\,177 \times 10^{-19}$ C	
electron mass	m_e	$9.109\,38 \times 10^{-31}$ kg	
	m_ec^2	0.510 999 MeV	
proton mass	m_p	$1.672\,622 \times 10^{-27}$ kg	
fine-structure constant	α	1/137.035 999	
Rydberg constant	R_∞	10 973 731.569 m^{-1}	
	$R_\infty c$	$3.289\,841\,960 \times 10^{15}$ Hz	
	$R_\infty hc$	13.605 69 eV	
Boltzmann constant	k	$1.380\,6 \times 10^{-23}$ J K^{-1}	

☐ Solids
🟦 Liquids
🟥 Gases
🟨 Artificially Prepared

Period	Group 1 IA	2 IIA	3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8	9 VIII	10	11 IB	12 IIB	13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	18 VIIIA
1	1 $^2S_{1/2}$ **H** Hydrogen 1.008* $1s$ 13.5984																	2 $^1S_0$ **He** Helium 4.002602 $1s^2$ 24.5874
2	3 $^2S_{1/2}$ **Li** Lithium 6.94* $1s^22s$ 5.3917	4 $^1S_0$ **Be** Beryllium 9.0121831 $1s^22s^2$ 9.3227											5 $^2P^\circ_{1/2}$ **B** Boron 10.81* $1s^22s^22p$ 8.2980	6 $^3P_0$ **C** Carbon 12.011* $1s^22s^22p^2$ 11.2603	7 $^4S^\circ_{3/2}$ **N** Nitrogen 14.007* $1s^22s^22p^3$ 14.5341	8 $^3P_2$ **O** Oxygen 15.999* $1s^22s^22p^4$ 13.6181	9 $^2P^\circ_{3/2}$ **F** Fluorine 18.99840316 $1s^22s^22p^5$ 17.4228	10 $^1S_0$ **Ne** Neon 20.1797 $1s^22s^22p^6$ 21.5645
3	11 $^2S_{1/2}$ **Na** Sodium 22.98976928 $[Ne]3s$ 5.1391	12 $^1S_0$ **Mg** Magnesium 24.305* $[Ne]3s^2$ 7.6462											13 $^2P^\circ_{1/2}$ **Al** Aluminum 26.9815385 $[Ne]3s^23p$ 5.9858	14 $^3P_0$ **Si** Silicon 28.085* $[Ne]3s^23p^2$ 8.1517	15 $^4S^\circ_{3/2}$ **P** Phosphorus 30.97376200 $[Ne]3s^23p^3$ 10.4867	16 $^3P_2$ **S** Sulfur 32.06* $[Ne]3s^23p^4$ 10.3600	17 $^2P^\circ_{3/2}$ **Cl** Chlorine 35.45* $[Ne]3s^23p^5$ 12.9676	18 $^1S_0$ **Ar** Argon 39.948 $[Ne]3s^23p^6$ 15.7596
4	19 $^2S_{1/2}$ **K** Potassium 39.0983 $[Ar]4s$ 4.3407	20 $^1S_0$ **Ca** Calcium 40.078 $[Ar]4s^2$ 6.1132	21 $^2D_{3/2}$ **Sc** Scandium 44.955908 $[Ar]3d4s^2$ 6.5615	22 $^3F_2$ **Ti** Titanium 47.867 $[Ar]3d^24s^2$ 6.8281	23 $^4F_{3/2}$ **V** Vanadium 50.9415 $[Ar]3d^34s^2$ 6.7462	24 $^7S_3$ **Cr** Chromium 51.9961 $[Ar]3d^54s$ 6.7665	25 $^6S_{5/2}$ **Mn** Manganese 54.938044 $[Ar]3d^54s^2$ 7.4340	26 $^5D_4$ **Fe** Iron 55.845 $[Ar]3d^64s^2$ 7.9025	27 $^4F_{9/2}$ **Co** Cobalt 58.933194 $[Ar]3d^74s^2$ 7.8810	28 $^3F_4$ **Ni** Nickel 58.6934 $[Ar]3d^84s^2$ 7.6399	29 $^2S_{1/2}$ **Cu** Copper 63.546 $[Ar]3d^{10}4s$ 7.7264	30 $^1S_0$ **Zn** Zinc 65.38 $[Ar]3d^{10}4s^2$ 9.3942	31 $^2P^\circ_{1/2}$ **Ga** Gallium 69.723 $[Ar]3d^{10}4s^24p$ 5.9993	32 $^3P_0$ **Ge** Germanium 72.630 $[Ar]3d^{10}4s^24p^2$ 7.8994	33 $^4S^\circ_{3/2}$ **As** Arsenic 74.921595 $[Ar]3d^{10}4s^24p^3$ 9.7886	34 $^3P_2$ **Se** Selenium 78.971 $[Ar]3d^{10}4s^24p^4$ 9.7524	35 $^2P^\circ_{3/2}$ **Br** Bromine 79.904* $[Ar]3d^{10}4s^24p^5$ 11.8138	36 $^1S_0$ **Kr** Krypton 83.798 $[Ar]3d^{10}4s^24p^6$ 13.9996
5	37 $^2S_{1/2}$ **Rb** Rubidium 85.4678 $[Kr]5s$ 4.1771	38 $^1S_0$ **Sr** Strontium 87.62 $[Kr]5s^2$ 5.6949	39 $^2D_{3/2}$ **Y** Yttrium 88.90584 $[Kr]4d5s^2$ 6.2173	40 $^3F_2$ **Zr** Zirconium 91.224 $[Kr]4d^25s^2$ 6.6339	41 $^6D_{1/2}$ **Nb** Niobium 92.90637 $[Kr]4d^45s$ 6.7589	42 $^7S_3$ **Mo** Molybdenum 95.95 $[Kr]4d^55s$ 7.0924	43 $^6S_{5/2}$ **Tc** Technetium (98) $[Kr]4d^55s^2$ 7.1194	44 $^5F_5$ **Ru** Ruthenium 101.07 $[Kr]4d^75s$ 7.3605	45 $^4F_{9/2}$ **Rh** Rhodium 102.90550 $[Kr]4d^85s$ 7.4589	46 $^1S_0$ **Pd** Palladium 106.42 $[Kr]4d^{10}$ 8.3369	47 $^2S_{1/2}$ **Ag** Silver 107.8682 $[Kr]4d^{10}5s$ 7.5762	48 $^1S_0$ **Cd** Cadmium 112.414 $[Kr]4d^{10}5s^2$ 8.9938	49 $^2P^\circ_{1/2}$ **In** Indium 114.818 $[Kr]4d^{10}5s^25p$ 5.7864	50 $^3P_0$ **Sn** Tin 118.710 $[Kr]4d^{10}5s^25p^2$ 7.3439	51 $^4S^\circ_{3/2}$ **Sb** Antimony 121.760 $[Kr]4d^{10}5s^25p^3$ 8.6084	52 $^3P_2$ **Te** Tellurium 127.60 $[Kr]4d^{10}5s^25p^4$ 9.0097	53 $^2P^\circ_{3/2}$ **I** Iodine 126.90447 $[Kr]4d^{10}5s^25p^5$ 10.4513	54 $^1S_0$ **Xe** Xenon 131.293 $[Kr]4d^{10}5s^25p^6$ 12.1298
6	55 $^2S_{1/2}$ **Cs** Cesium 132.9054520 $[Xe]6s$ 3.8939	56 $^1S_0$ **Ba** Barium 137.327 $[Xe]6s^2$ 5.2117		72 $^3F_2$ **Hf** Hafnium 178.49 $[Xe]4f^{14}5d^26s^2$ 6.8251	73 $^4F_{3/2}$ **Ta** Tantalum 180.94788 $[Xe]4f^{14}5d^36s^2$ 7.5496	74 $^5D_0$ **W** Tungsten 183.84 $[Xe]4f^{14}5d^46s^2$ 7.8640	75 $^6S_{5/2}$ **Re** Rhenium 186.207 $[Xe]4f^{14}5d^56s^2$ 7.8335	76 $^5D_4$ **Os** Osmium 190.23 $[Xe]4f^{14}5d^66s^2$ 8.4382	77 $^4F_{9/2}$ **Ir** Iridium 192.217 $[Xe]4f^{14}5d^76s^2$ 8.9670	78 $^3D_3$ **Pt** Platinum 195.084 $[Xe]4f^{14}5d^96s$ 8.9588	79 $^2S_{1/2}$ **Au** Gold 196.966569 $[Xe]4f^{14}5d^{10}6s$ 9.2256	80 $^1S_0$ **Hg** Mercury 200.592 $[Xe]4f^{14}5d^{10}6s^2$ 10.4375	81 $^2P^\circ_{1/2}$ **Tl** Thallium 204.38* $[Hg]6p$ 6.1083	82 $^3P_0$ **Pb** Lead 207.2 $[Hg]6p^2$ 7.4167	83 $^4S^\circ_{3/2}$ **Bi** Bismuth 208.98040 $[Hg]6p^3$ 7.2855	84 $^3P_2$ **Po** Polonium (209) $[Hg]6p^4$ 8.414	85 $^2P^\circ_{3/2}$ **At** Astatine (210) $[Hg]6p^5$ 9.31751	86 $^1S_0$ **Rn** Radon (222) $[Hg]6p^6$ 10.7485
7	87 $^2S_{1/2}$ **Fr** Francium (223) $[Rn]7s$ 4.0727	88 $^1S_0$ **Ra** Radium (226) $[Rn]7s^2$ 5.2784		104 $^3F_2$ **Rf** Rutherfordium (267) $[Rn]5f^{14}6d^27s^2$ 6.01	105 $^4F_{3/2}$ **Db** Dubnium (268) $[Rn]5f^{14}6d^37s^2$ 6.8	106 **Sg** Seaborgium (271) $[Rn]5f^{14}6d^47s^2$ 7.8	107 **Bh** Bohrium (272) $[Rn]5f^{14}6d^57s^2$ 7.7	108 **Hs** Hassium (270) $[Rn]5f^{14}6d^67s^2$ 7.6	109 **Mt** Meitnerium (276)	110 **Ds** Darmstadtium (281)	111 **Rg** Roentgenium (280)	112 **Cn** Copernicium (285)	113 **Uut** Ununtrium (284)	114 **Fl** Flerovium (289)	115 **Uup** Ununpentium (288)	116 **Lv** Livermorium (293)	117 **Uus** Ununseptium (294)	118 **Uuo** Ununoctium (294)

Lanthanides	57 $^2D_{3/2}$ **La** Lanthanum 138.90547 $[Xe]5d6s^2$ 5.5769	58 $^1G^\circ_4$ **Ce** Cerium 140.116 $[Xe]4f5d6s^2$ 5.5386	59 $^4I^\circ_{9/2}$ **Pr** Praseodymium 140.907 $[Xe]4f^36s^2$ 5.473	60 $^5I_4$ **Nd** Neodymium 144.242 $[Xe]4f^46s^2$ 5.5250	61 $^6H^\circ_{5/2}$ **Pm** Promethium (145) $[Xe]4f^56s^2$ 5.582	62 $^7F_0$ **Sm** Samarium 150.36 $[Xe]4f^66s^2$ 5.6437	63 $^8S^\circ_{7/2}$ **Eu** Europium 151.964 $[Xe]4f^76s^2$ 5.6704	64 $^9D^\circ_2$ **Gd** Gadolinium 157.25 $[Xe]4f^75d6s^2$ 6.1498	65 $^6H^\circ_{15/2}$ **Tb** Terbium 158.92535 $[Xe]4f^96s^2$ 5.8638	66 $^5I_8$ **Dy** Dysprosium 162.500 $[Xe]4f^{10}6s^2$ 5.9391	67 $^4I^\circ_{15/2}$ **Ho** Holmium 164.93033 $[Xe]4f^{11}6s^2$ 6.0215	68 $^3H_6$ **Er** Erbium 167.259 $[Xe]4f^{12}6s^2$ 6.1077	69 $^2F^\circ_{7/2}$ **Tm** Thulium 168.93422 $[Xe]4f^{13}6s^2$ 6.1843	70 $^1S_0$ **Yb** Ytterbium 173.054 $[Xe]4f^{14}6s^2$ 6.2542	71 $^2D_{3/2}$ **Lu** Lutetium 174.9668 $[Xe]4f^{14}5d6s^2$ 5.4259
Actinides	89 $^2D_{3/2}$ **Ac** Actinium (227) $[Rn]6d7s^2$ 5.3802	90 $^3F_2$ **Th** Thorium 232.0377 $[Rn]6d^27s^2$ 6.3067	91 $^4K_{11/2}$ **Pa** Protactinium 231.03588 $[Rn]5f^26d7s^2$ 5.89	92 $^5L^\circ_6$ **U** Uranium 238.02891 $[Rn]5f^36d7s^2$ 6.1941	93 $^6L_{11/2}$ **Np** Neptunium (237) $[Rn]5f^46d7s^2$ 6.2655	94 $^7F_0$ **Pu** Plutonium (244) $[Rn]5f^67s^2$ 6.0258	95 $^8S^\circ_{7/2}$ **Am** Americium (243) $[Rn]5f^77s^2$ 5.9738	96 $^9D^\circ_2$ **Cm** Curium (247) $[Rn]5f^76d7s^2$ 5.9914	97 $^6H^\circ_{15/2}$ **Bk** Berkelium (247) $[Rn]5f^97s^2$ 6.1978	98 $^5I_8$ **Cf** Californium (251) $[Rn]5f^{10}7s^2$ 6.2817	99 $^4I^\circ_{15/2}$ **Es** Einsteinium (252) $[Rn]5f^{11}7s^2$ 6.3676	100 $^3H_6$ **Fm** Fermium (257) $[Rn]5f^{12}7s^2$ 6.50	101 $^2F^\circ_{7/2}$ **Md** Mendelevium (258) $[Rn]5f^{13}7s^2$ 6.58	102 $^1S_0$ **No** Nobelium (259) $[Rn]5f^{14}7s^2$ 6.65	103 $^2P^\circ_{1/2}$ **Lr** Lawrencium (262) $[Rn]5f^{14}7s^27p$ 4.90

Atomic Number	58
Ground-state Level	$^1G^\circ_4$
Symbol	**Ce**
Name	Cerium
Standard Atomic Weight†	140.116
Ground-state Configuration	$[Xe]4f5d6s^2$
Ionization Energy (eV)	5.5386

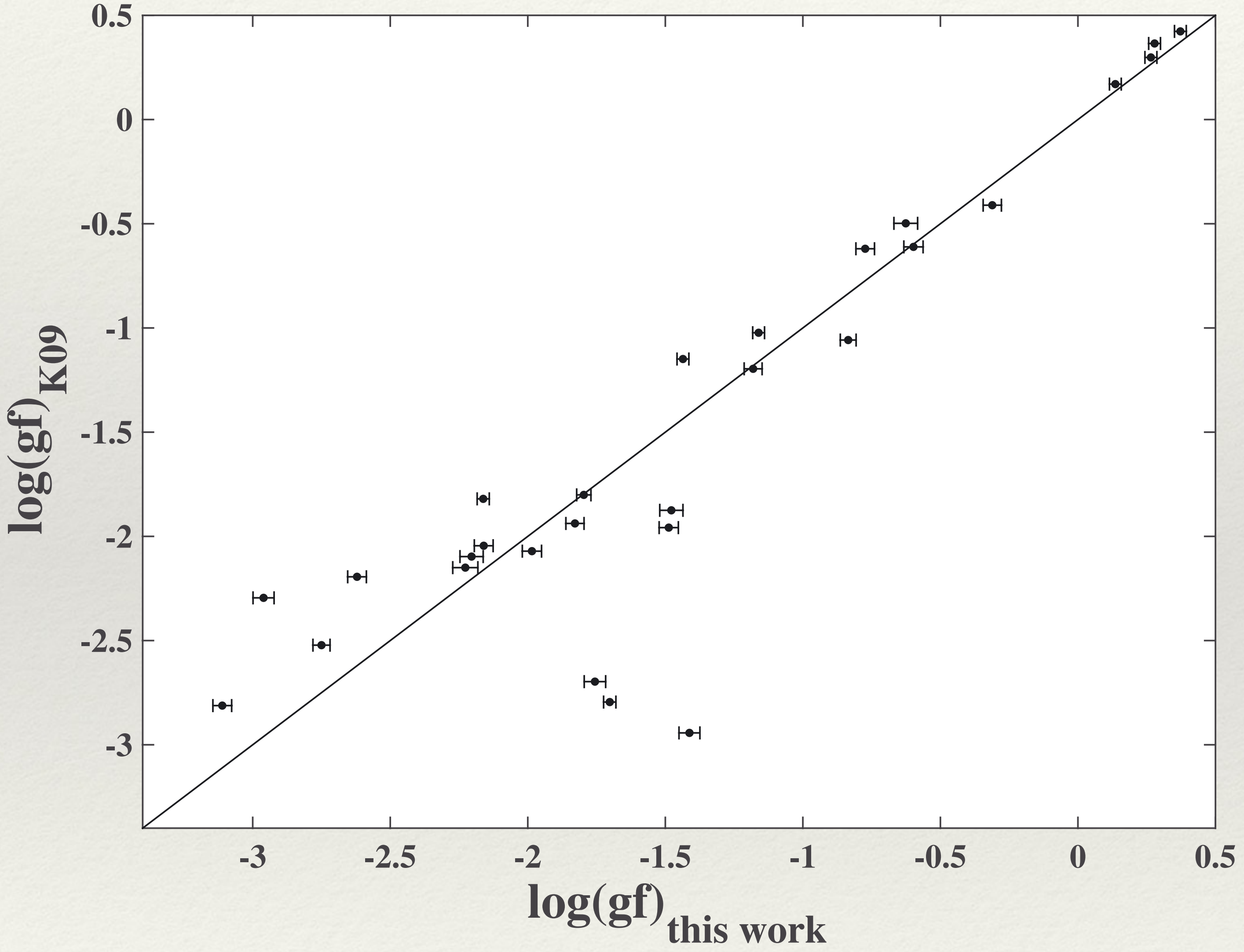
†Based upon ^{12}C. () indicates the mass number of the longest-lived isotope.

*IUPAC conventional atomic weights; standard atomic weights for these elements are expressed in intervals; see iupac.org for an explanation and values.

For a description of the data, visit physics.nist.gov/data

NIST SP 966 (September 2014)

Results for Sc I

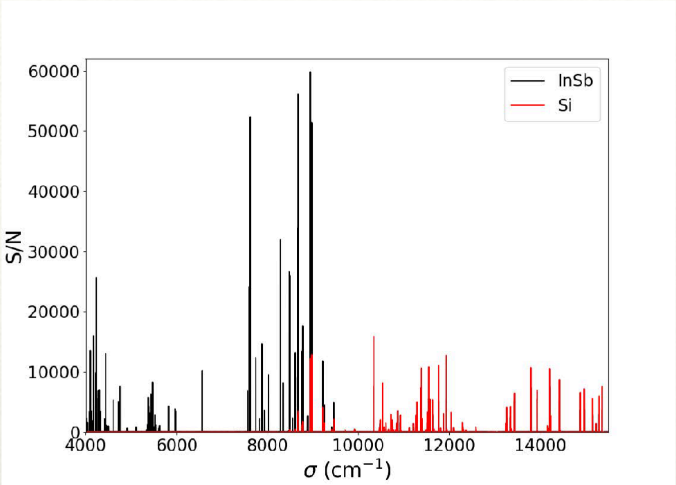


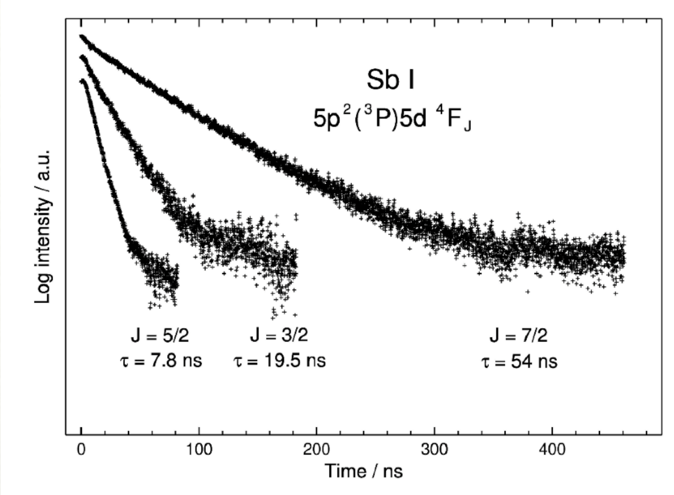
The experimental results are compared to the calculations by Kurucz (2009)

Lifetimes and spectra for Y I and La I are measured and being analysed

Pehlivan et al., (2015)

Uncertainties





Remember: $$A_{ul} = \frac{BF_{ul}}{\tau_u}$$

Uncertainties for experimental data:

Branching fractions: 0-30%

Radiative lifetimes: 5-15%

Experimental f-values can be obtained with uncertainties down to 5%

Uncertainties for theoretical data are harder to estimate, and vary among lines in a calculation.

Parity forbidden lines in near-IR

An important class of infrared lines are parity forbidden transitions (E2 and M1), observed in nebula and low density plasmas.

Low transition rates (A around 1 s^{-1}*)*

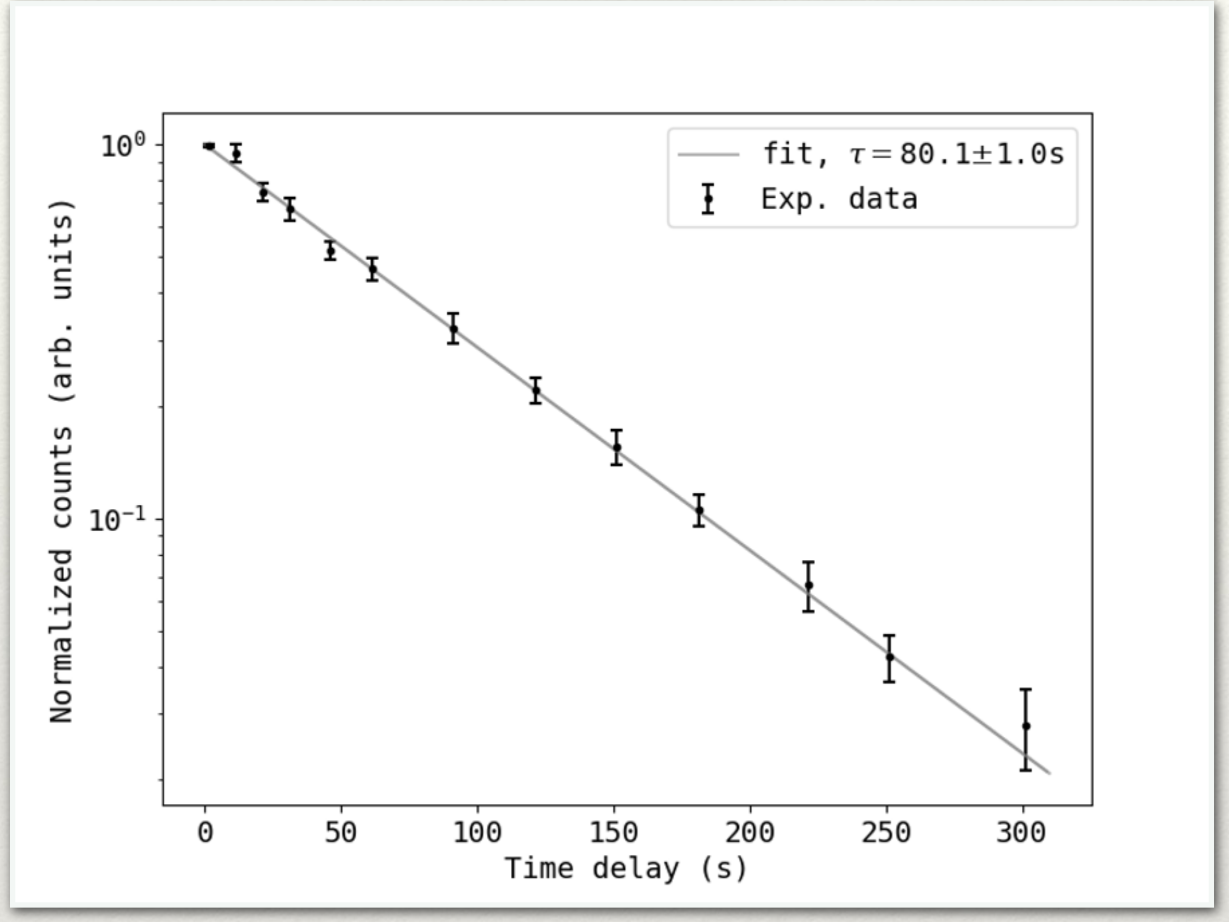
Long radiative lifetimes (several seconds)

Sensitive to collisions

$$A_{ul} = \frac{BF_{ul}}{\tau_u}$$

Can be measured using selective methods at storage rings (e.g. DESIREE @ Stockholm university) combined with astronomical observations of low-density plasmas (Eta Carinae).

Preliminary results for Ba II : $5d^2D_{3/2}$



The pump-probe technique has successfully been developed for the Ba+ ions at DESIREE.

- Ion beam lifetime measured to 500s.
- Effect from repopulation and cascades is very small.
- An uncertainty of a few percent can be reached for ideal systems.
- For $5d^2D_{3/2}$ we reach a lifetime $\tau = 80 \pm 1$ s

Technique will be applied to more complex systems such as FeII and Ni II with astrophysical importance .

Summary

Experiments can provide accurate wavelengths for most lines for an ion, also for complex spectra. Level energies require analysis.

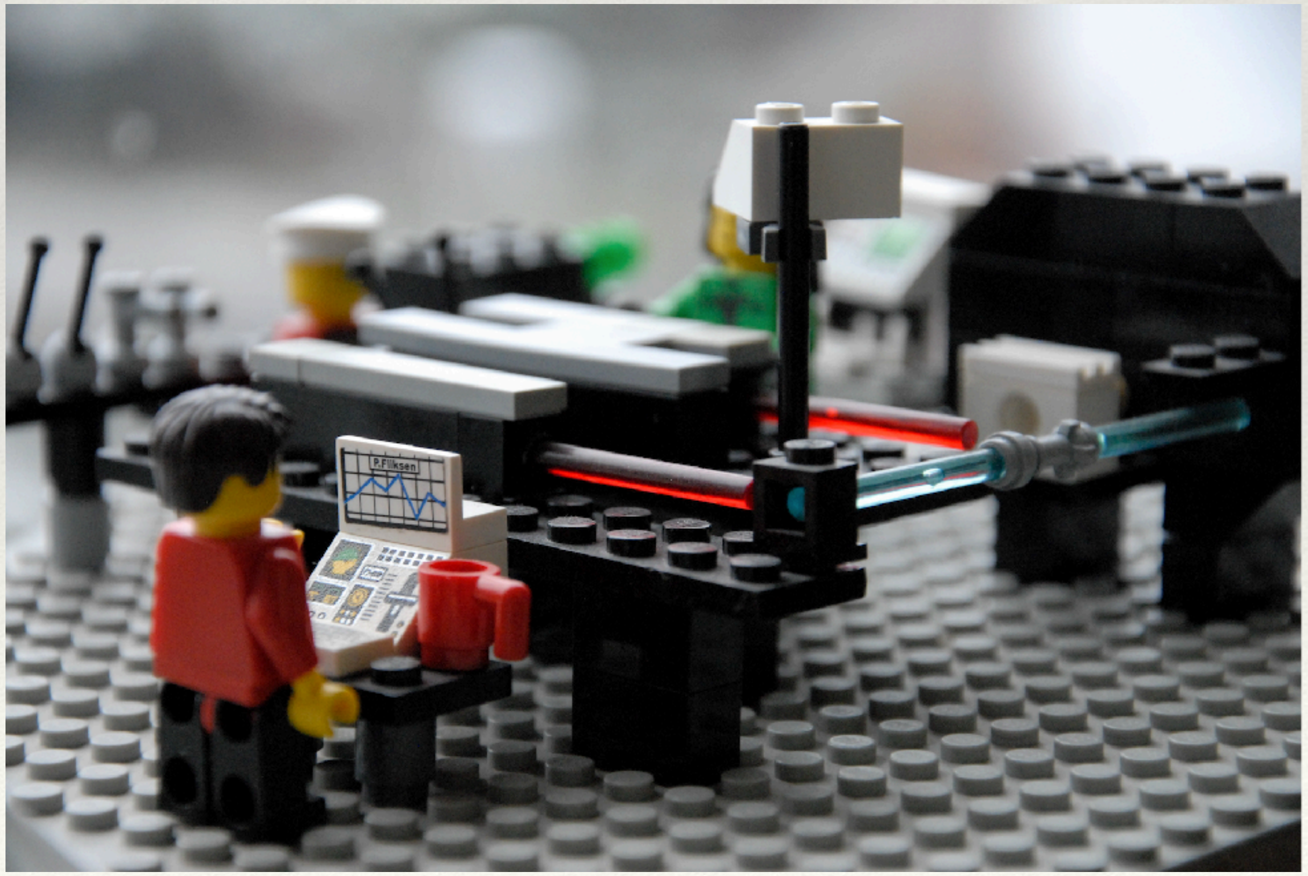
Accurate line strengths are derived for selected sets of transitions, to an accuracy of 5%
The majority of line intensities are to be provided by calculations. Different approach depending on target ion.

Near-infrared experimental data has been provided for Mg I, Sc I, Al I and Si I and Si II

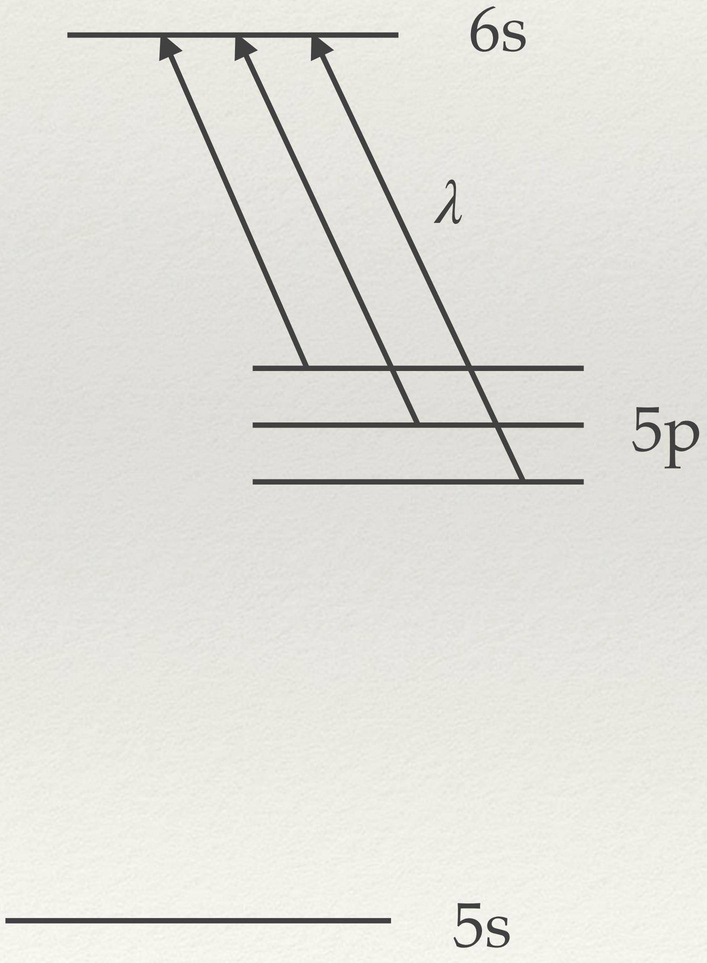
Analysis in progress: Y I and La I (IR), Zr II

Ongoing: Ce I and Ce II. We investigate an approach to apply a tuning technique to merge the theoretical and experimental linelists, with the extension to Ce III using additional light source.

Forbidden lines can be measured using a stored ion beam.



Term analysis - new levels



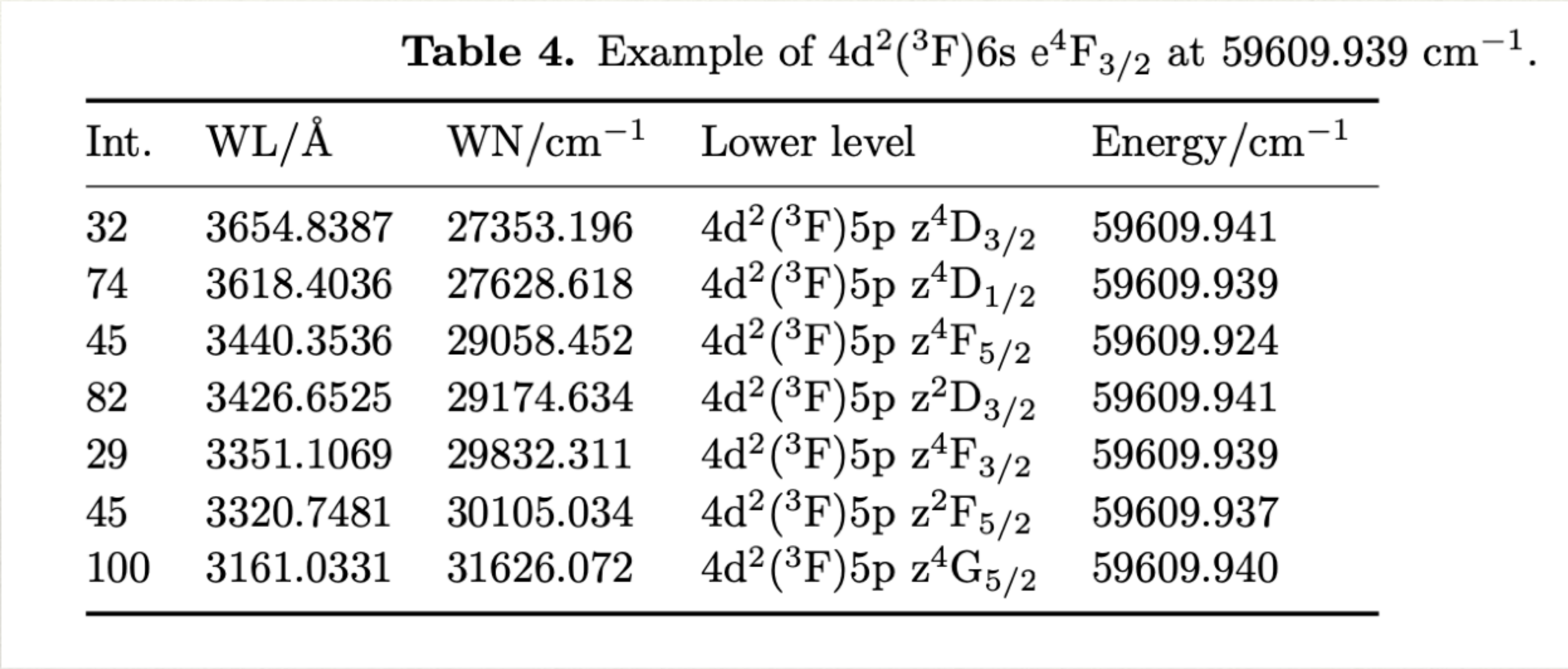


Table 4. Example of $4d^2(^3F)6s\ e^4F_{3/2}$ at 59609.939 cm^{-1}.

Int.	WL/Å	WN/cm^{-1}	Lower level	Energy/cm^{-1}
32	3654.8387	27353.196	$4d^2(^3F)5p\ z^4D_{3/2}$	59609.941
74	3618.4036	27628.618	$4d^2(^3F)5p\ z^4D_{1/2}$	59609.939
45	3440.3536	29058.452	$4d^2(^3F)5p\ z^4F_{5/2}$	59609.924
82	3426.6525	29174.634	$4d^2(^3F)5p\ z^2D_{3/2}$	59609.941
29	3351.1069	29832.311	$4d^2(^3F)5p\ z^4F_{3/2}$	59609.939
45	3320.7481	30105.034	$4d^2(^3F)5p\ z^2F_{5/2}$	59609.937
100	3161.0331	31626.072	$4d^2(^3F)5p\ z^4G_{5/2}$	59609.940

Hyperfine structure

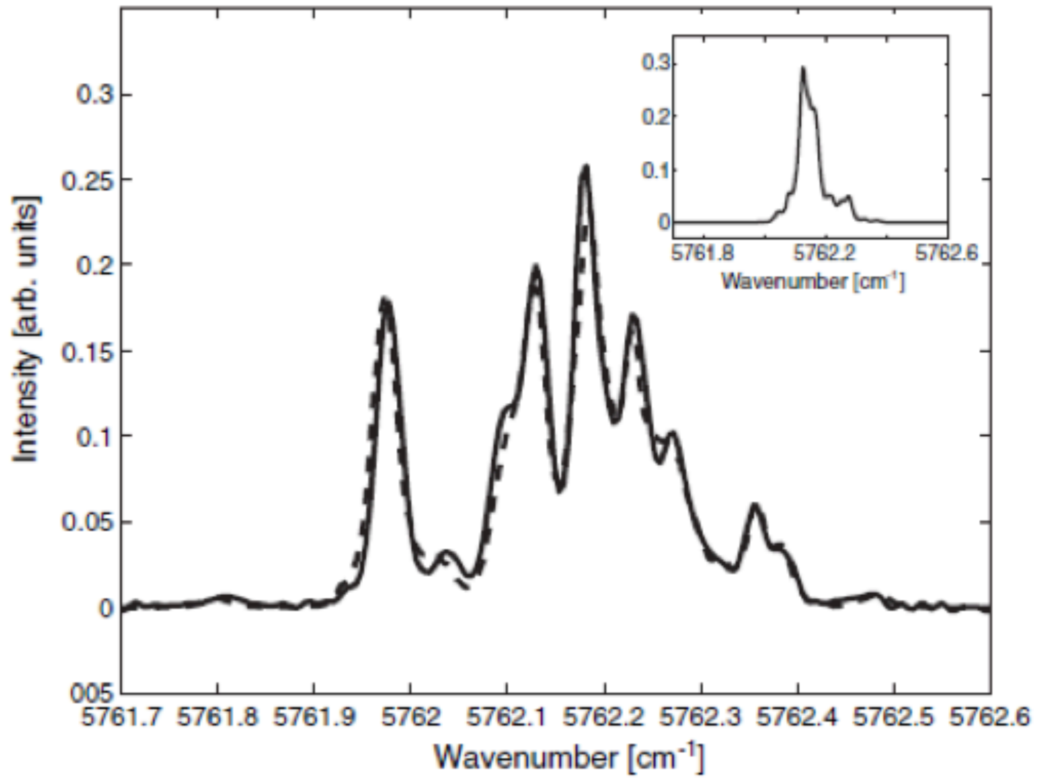
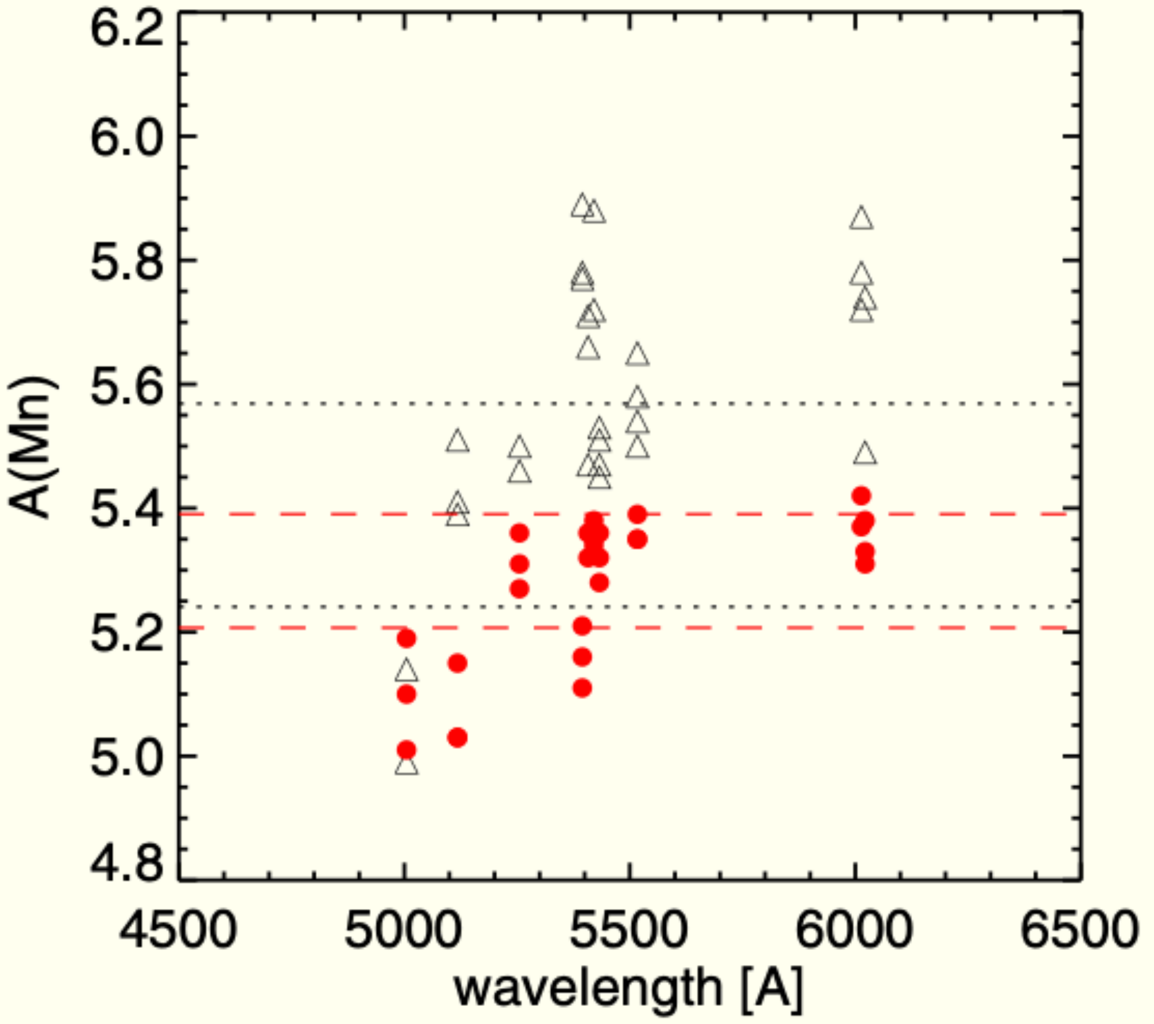


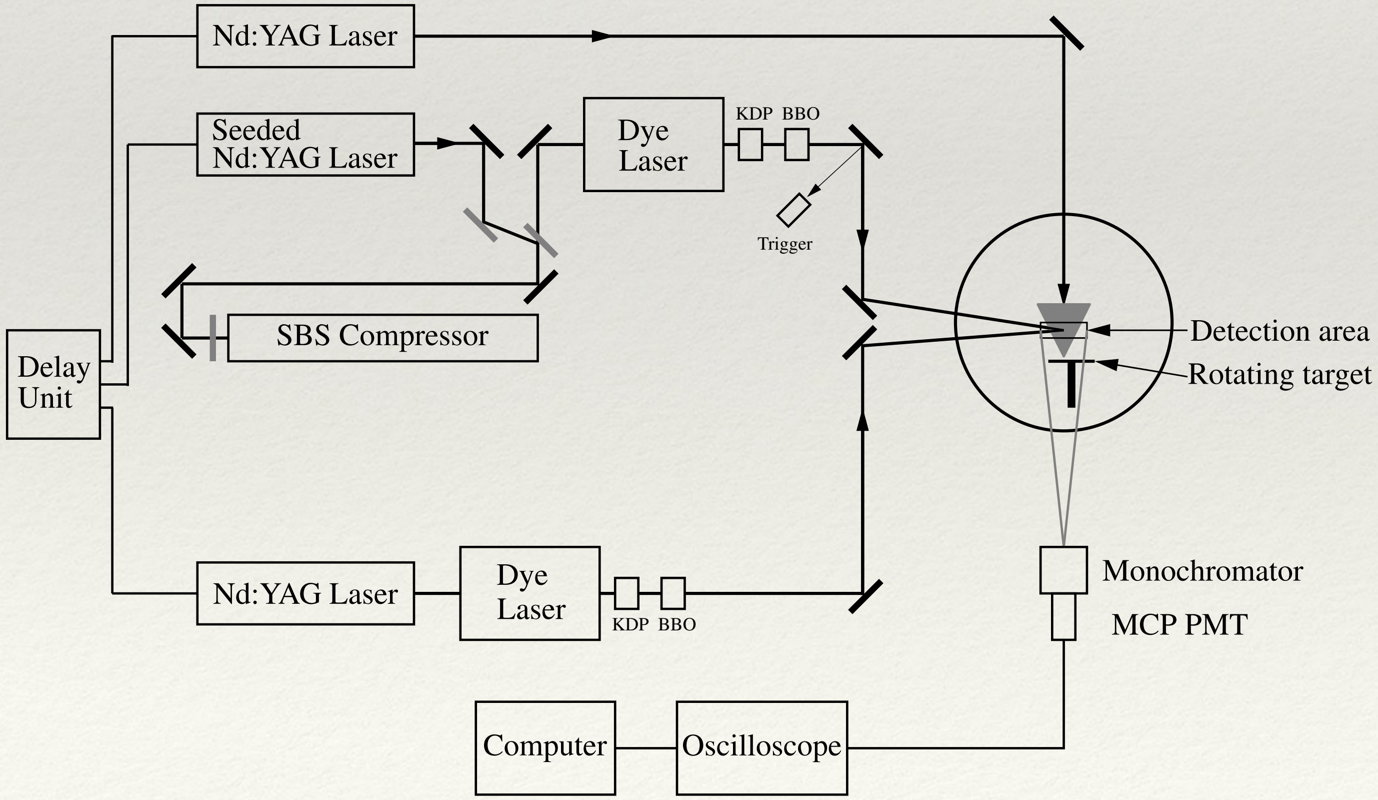
Figure 4. Experimental spectrum (solid line) compared to the *CHA* spectrum (dashed line) for the e^{6}D$_{5/2}$–w^{6}F transitions (the 17349 Å line). The *Diagonal* spectrum is presented as an inset plot.

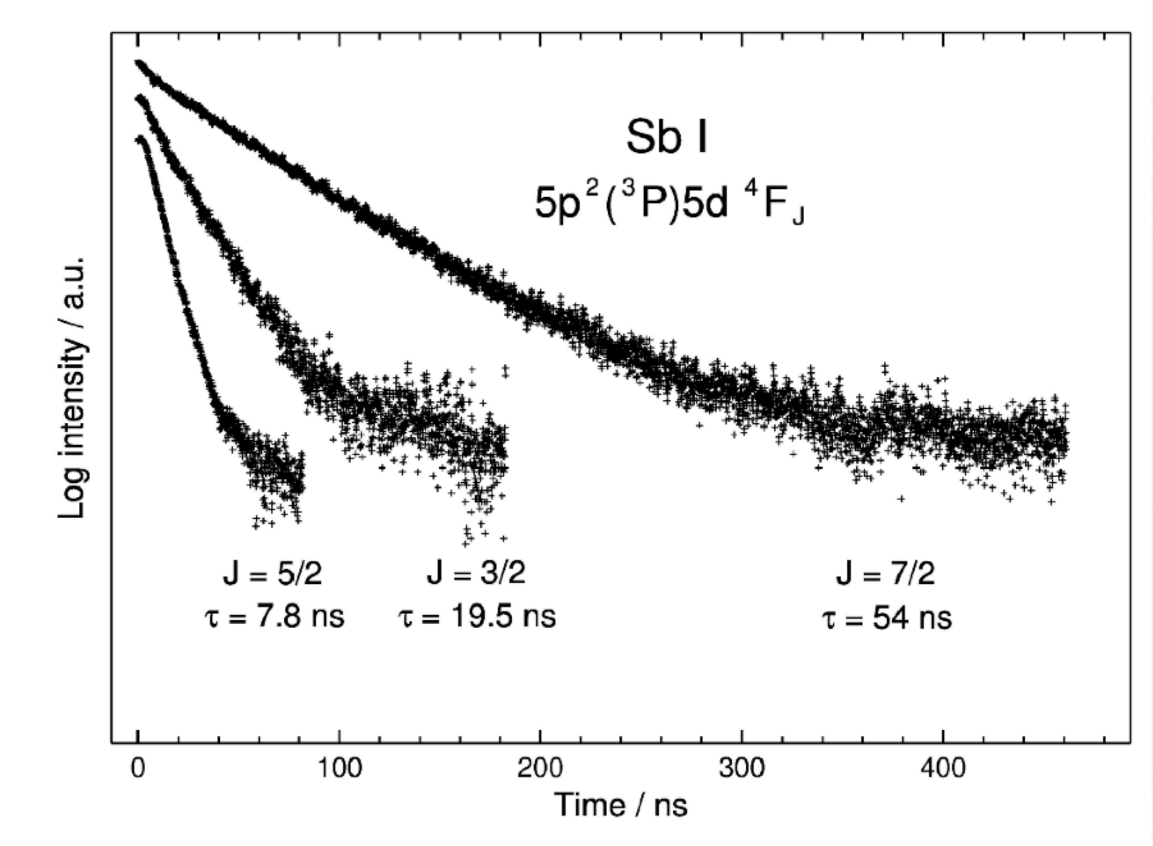


The effect from hyperfine structure can affect the derived abundance and is more prominent in the near-infrared wavelength region

Andersson et al. (2015) and Jofre et al. (2015)

Laser induced plasma probed with short pulses (1ns)





Hartman et al, (2010)

Advice when asking for atomic data

To maximize the outcome of a request for atomic data:
- Be specific in terms of element, ionization, wavelength region, excitation
- If possible, specify a desired accuracy
- Provide a scientific motivation

No : We need all iron group elements, for spectra I, II and III

Yes : We need the oscillator strength for the Ni I line blending the O I 6300Å line to an accuracy of 0.02 dex. It is important for the longstanding controversy of the solar abundance of oxygen.