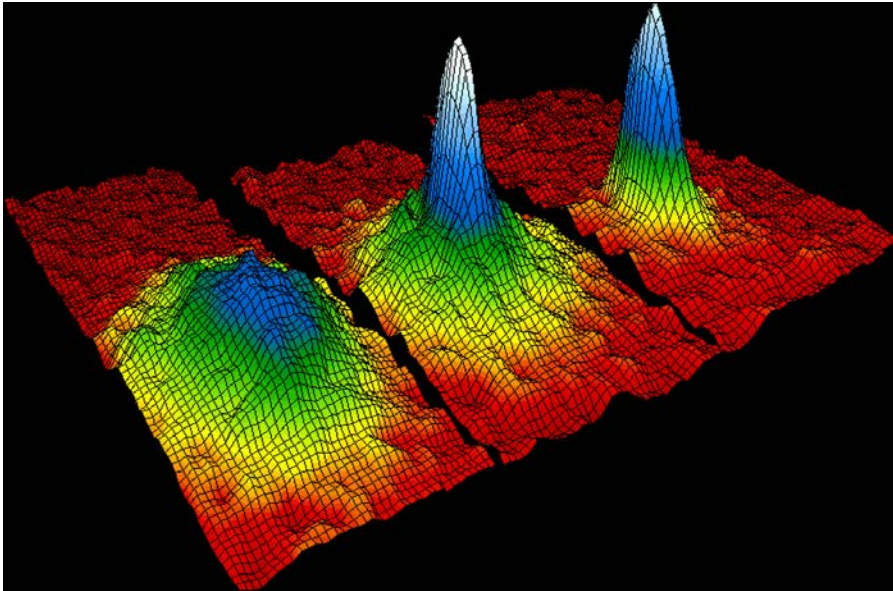


PHYS598 AQG

Introduction to the course



First quantum gas in dilute atomic vapors
 ^{87}Rb BEC : Wieman / Cornell group (1995)

- *Logistics*
- *A bit about the course material*

Logistics for the course

Website: <https://courses.physics.illinois.edu/phys598AQG/fa2017/>

The course site has info regarding:

- General info (personnel, text, office hours,...)
- Assessment (HWs = 60%, project = 35%, seminars = 5%)
- Course schedule
- Homework assignments
- Final paper
- Various and sundry

The course subject

Atomic Physics and Atomic Quantum Gases

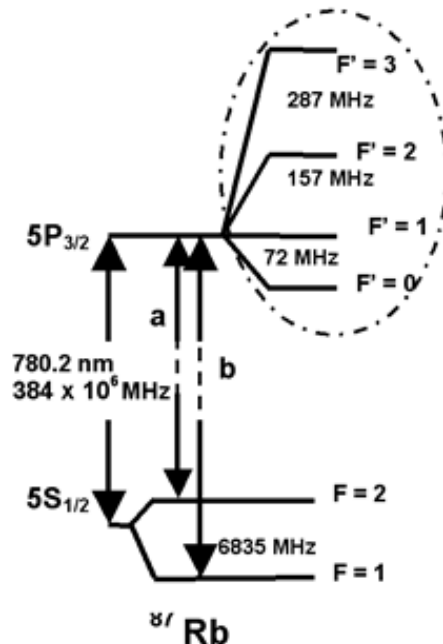
The course subject

Atomic Physics and Atomic Quantum Gases

We'll study everything that's made up of atoms **✗ NO**

→ Most of this falls under the category of “condensed matter”

We'll focus on the simple case of atoms isolated from an environment



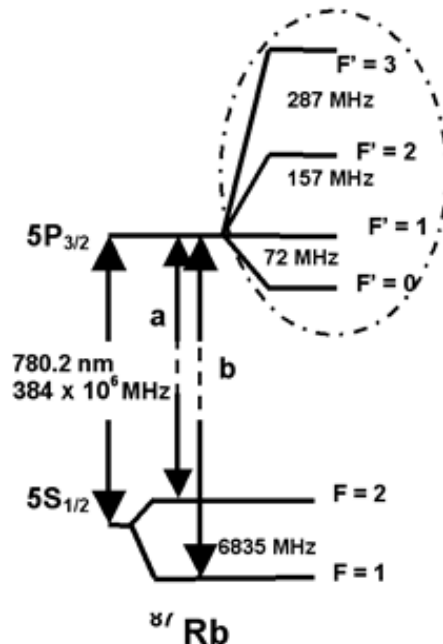
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What determines their energy level structure?
(First 3 weeks of the course)

How can we exert control over their various
degrees of freedom?
(~ Weeks 4-9)

These ideas can also be applied to “artificial” atoms:
quantum dots, NV centers, superconducting circuits
(fluxonium, qutrit, transmons)

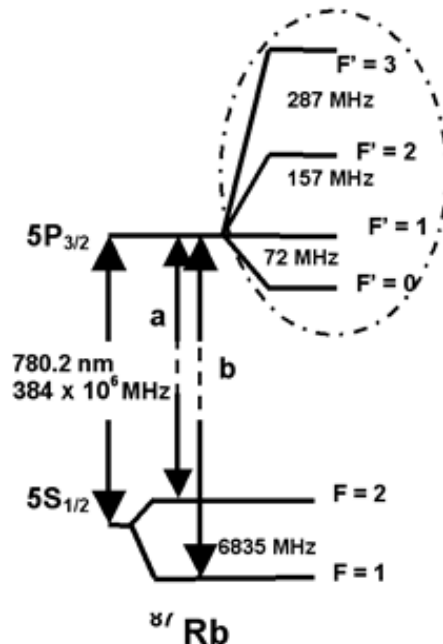
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(First 3 weeks of the course)

How can we exert control over their various degrees of freedom?
(~ Weeks 4-9)

What kind of novel phenomena can we study in many-atom systems?

Topics to be covered

Atomic structure: hydrogen, helium, alkali atoms; fine structure, hyperfine structure, Lamb shift, Zeeman effect

Two-level systems: Rabi problem, density matrices & open quantum systems, optical Bloch equations, adiabatic processes

Light/atom interactions: dipole selection rules, semiclassical treatment, quantum treatment, laser-cooling, magneto-optical traps, sub-Doppler cooling, ac Stark effect, optical traps, cavity QED

Ultracold atoms: magnetic trapping, evaporative cooling, ultracold collisions, Feshbach resonances, BECs & Fermi gases

Quantum simulation: optical lattices, cold-atom Hubbard models, special properties of some alkaline earth atoms and rare earth atoms, ultracold molecules, ions, and Rydberg atoms

AMO Physics more broadly

(Atomical, Molecular, & Optical Physics)

Many, many active research fronts

- quantum gases**: of atoms, molecules, of various quasi-particles, etc.
- quantum simulation**: many-body physics, connections to condensed matter
- trapped ions**: precise measurements, quantum optics, quantum computing, quantum simulation
- cold molecules**: precision measurements, cold chemistry, quantum computing, quantum simulation
- Rydberg atoms**: quantum computing, sensing of fields, novel quantum states
- expansion of the "toolbox"**: new atomic species for cooling, new capabilities
- quantum optics**: cavity QED, nonlinear optics
- quantum communications**: quantum repeaters, quantum memories, entangled state generation, etc.
- optical sciences**: photonics, phononics, quantum dots, laser physics, high-harmonic generation, NV centers, etc.
- precision measurement of fundamental constants**: PNC, EDM, dark energy searches
- sensing**: clocks, gyroscopes, interferometers, ATTA
- atom optics**: quantum-limited measurements, atomtronics, etc.
- and more (ion-atom collisions, atom-molecule collisions, ultracold plasmas)

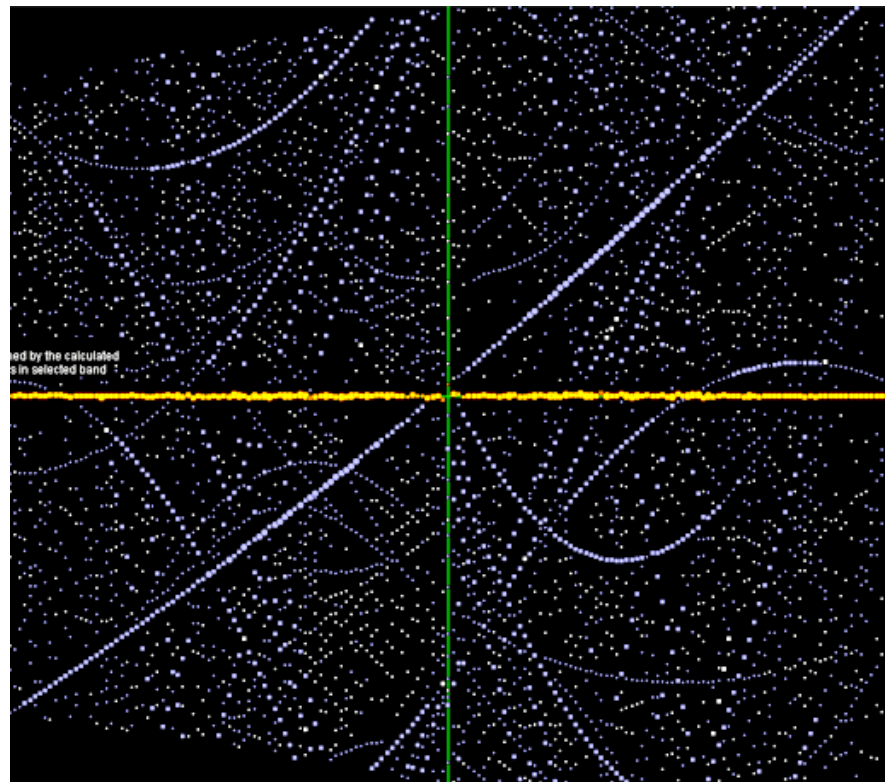
Atomic Molecular & Optical physics

2 central themes:
spectroscopy

measuring physical quantities
with extreme precision and accuracy

Some local history

Loomis-Wood diagram
of molecular spectra



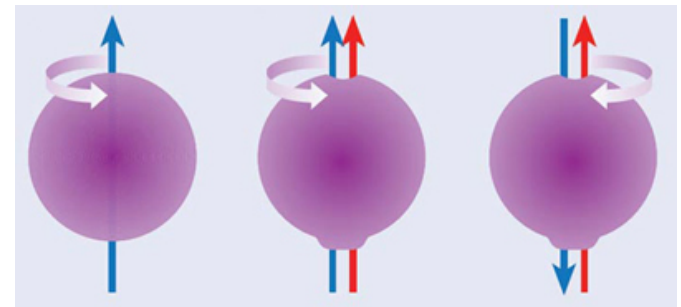
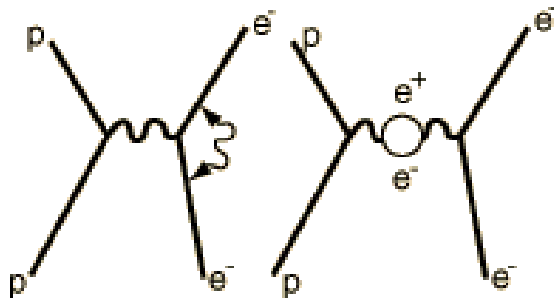
Atomic Molecular & Optical physics

2 central themes:
spectroscopy

measuring physical quantities
with extreme precision and accuracy

Precise measurements tell us a lot about nature

- Development of quantum theory
- Development of QED (Lamb shift measurement)
- Search for physics beyond the Standard Model



Atomic Molecular & Optical physics

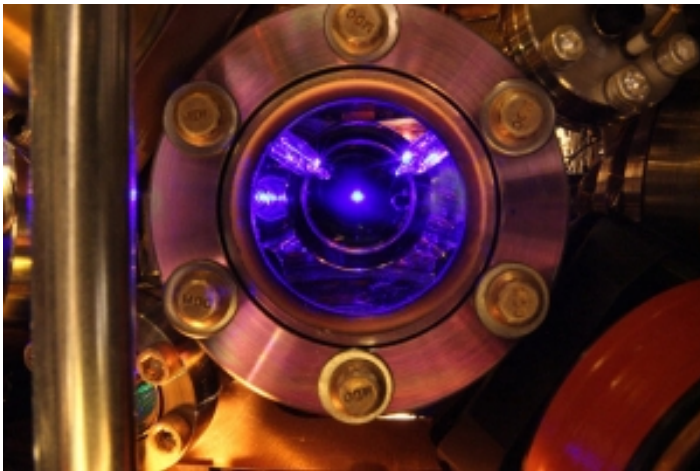
2 central themes: spectroscopy

measuring physical quantities
with extreme precision and accuracy

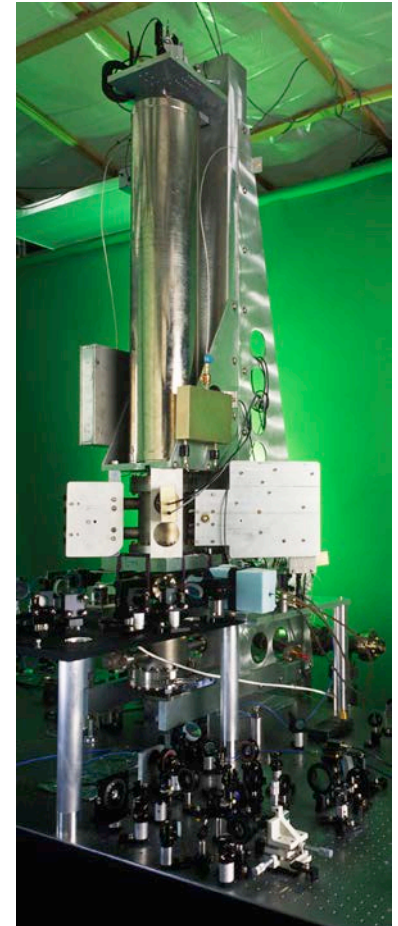
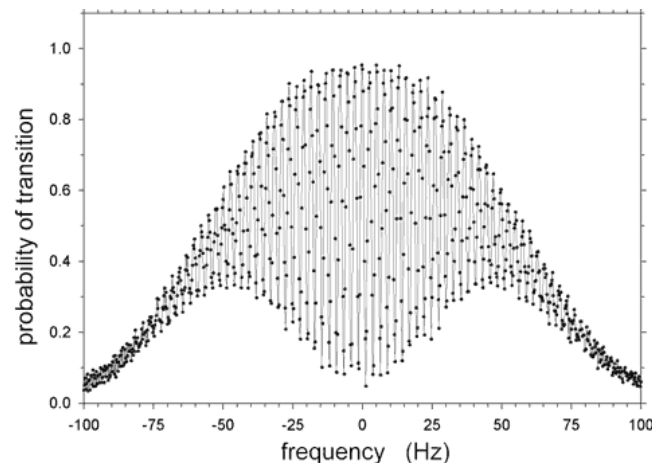
Precise measurements also tell us a lot
about our environment

- SI definition of the second – application: GPS

Sr lattice clock JILA, Boulder



cesium clock at NIST Boulder



Atomic Molecular & Optical physics

2 central themes:

spectroscopy

measuring physical quantities
with extreme precision and accuracy

Precise measurements also tell us a lot
about our environment

- SI definition of the second – application: GPS
- Global geodesy
- Precision magnetometry
- Search for non-Newtonian physics

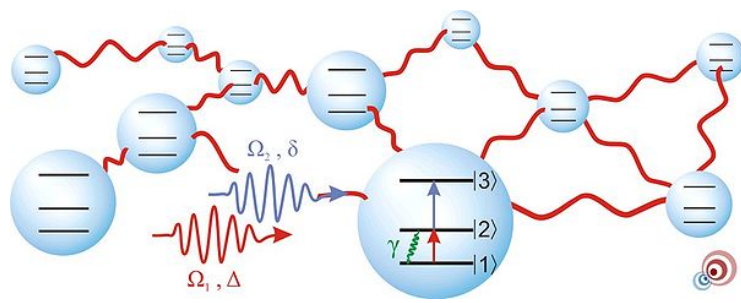
Atomic Molecular & Optical physics

2 central themes: coherent control

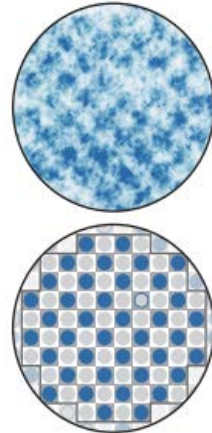
AMO systems are the most well-controlled, well-isolated quantum systems we have to study

→ Great place to study emergent physics

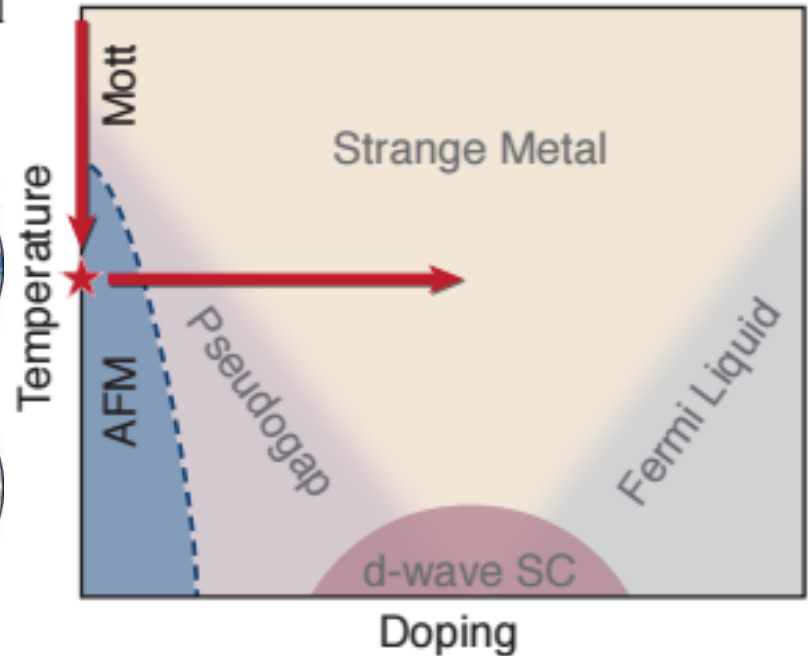
strongly correlated quantum matter and non-equilibrium dynamics



Weidemüller group, Heidelberg



Greiner group, Harvard



AMO Physics

- Rich variety of possible “building blocks”

- neutral atoms

- bosons/fermions, various properties

- ions (remove one electron)

- Rydberg atoms (nearly ionize)

- molecules (combine 2 or more atoms)

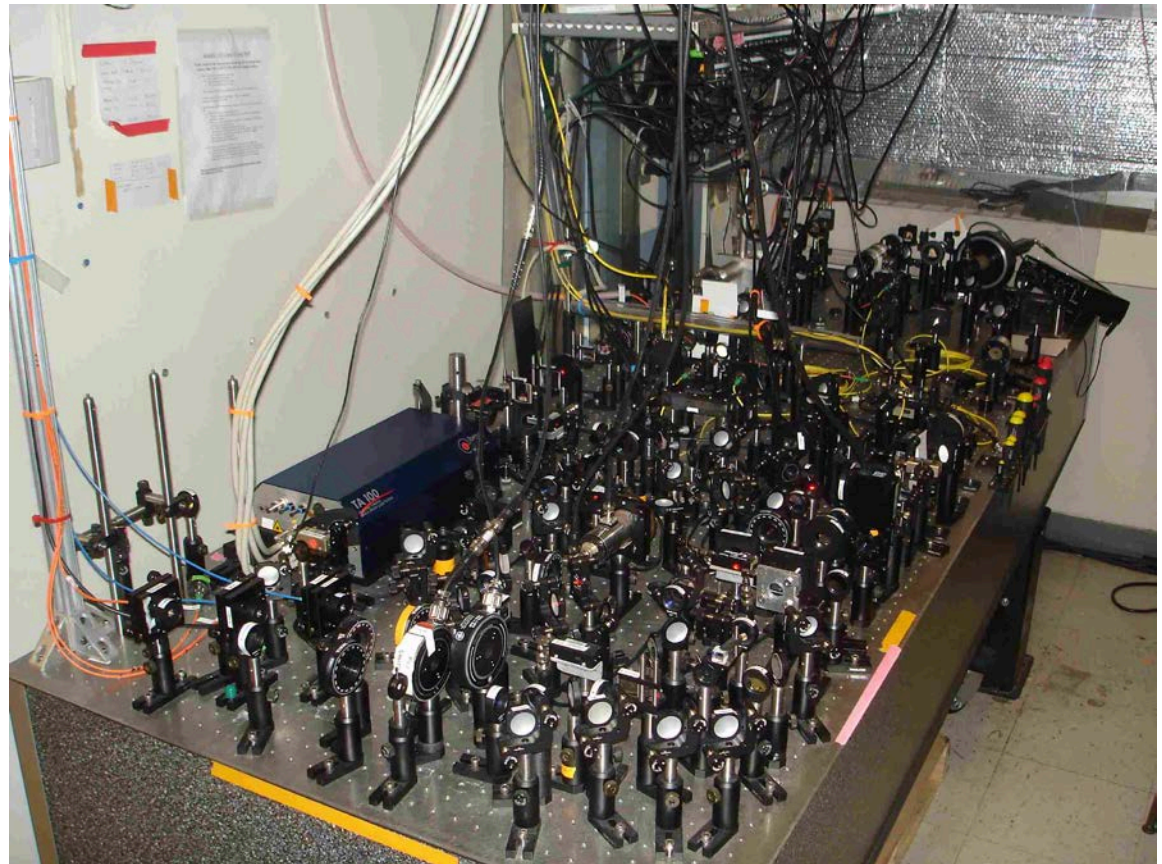
- artificial atoms (NVs, quantum dots, SC qubits,...)

- cavity QED, “quantum objects” (cantilevers, membranes,...)

Can study these systems separately, or combine the pieces in various ways

Research activity in the U.S.

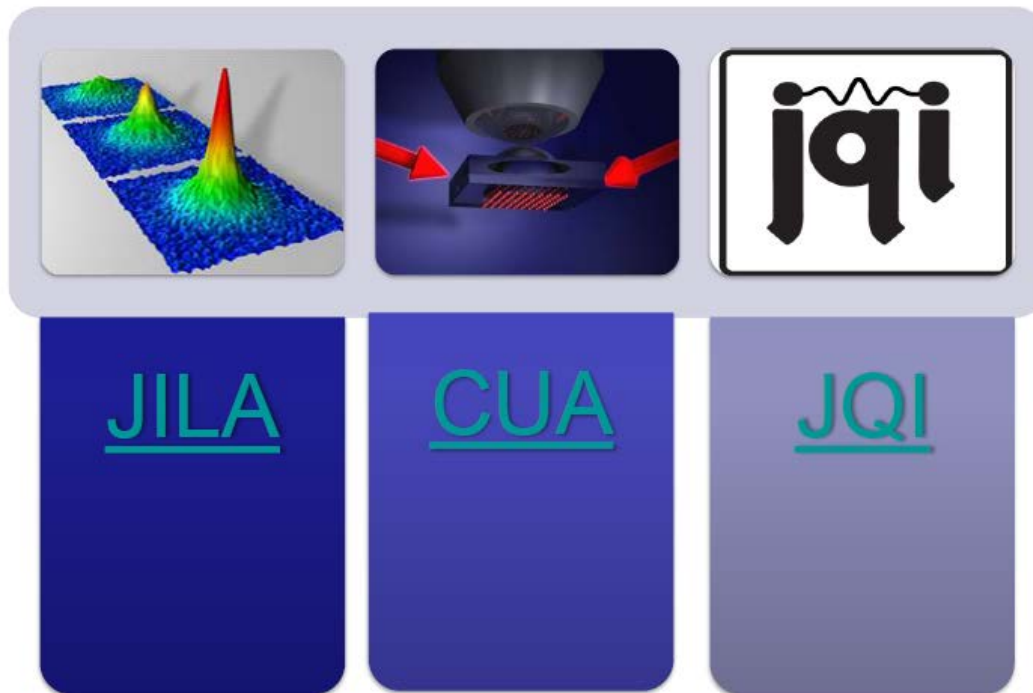
The scale of experiments is often small (a few students and a few optical tables), so there are research groups at most R1 institutions.



Li expt. optics table, Ketterle group, MIT

Research activity in the U.S.

There are a few “hot spots” in the US
(the ones shown are active PFCs)



JILA & JQI both
associated with
NIST (formerly NBS)

There are also many, many groups worldwide in
Europe, China, Japan, Korea, Australia, Canada, Singapore,...

<https://ucan.physics.utoronto.ca/Groups>

Where to start?

- Many atoms have been laser-cooled and trapped
 - let's start with hydrogen

hydrogen 1 H 1.0079																							helium 2 He 4.0026						
lithium 3 Li 6.941	beryllium 4 Be 9.0122																							boron 5 B 10.811	carbon 6 C 12.011	nitrogen 7 N 14.007	oxygen 8 O 15.999	fluorine 9 F 18.998	neon 10 Ne 20.180
sodium 11 Na 22.990	magnesium 12 Mg 24.305																							aluminum 13 Al 26.982	silicon 14 Si 28.086	phosphorus 15 P 30.974	sulfur 16 S 32.065	chlorine 17 Cl 35.453	argon 18 Ar 39.948
potassium 19 K 39.098	calcium 20 Ca 40.078	scandium 21 Sc 44.956	titanium 22 Ti 47.867	vanadium 23 V 50.942	chromium 24 Cr 51.996	manganese 25 Mn 54.938	iron 26 Fe 55.845	cobalt 27 Co 58.933	nickel 28 Ni 58.693	copper 29 Cu 63.546	zinc 30 Zn 65.39	gallium 31 Ga 69.723	germanium 32 Ge 72.61	arsenic 33 As 74.922	selecnium 34 Se 78.96	bromine 35 Br 79.904	krpton 36 Kr 83.80												
rubidium 37 Rb 85.468	strontium 38 Sr 87.62	yttrium 39 Y 88.906	zirconium 40 Zr 91.224	niobium 41 Nb 92.906	molybdenum 42 Mo 95.94	technetium 43 Tc [98]	ruthenium 44 Ru 101.07	rhodium 45 Rh 102.91	pdadium 46 Pd 106.42	silver 47 Ag 107.87	cadmium 48 Cd 112.41	indium 49 In 114.82	tin 50 Sn 118.71	antimony 51 Sb 121.76	tellurium 52 Te 127.60	iodine 53 I 126.90	xenon 54 Xe 131.29												
cesium 55 Cs 132.91	barium 56 Ba 137.33	lanthanum 57 Lu 174.97	hafnium 72 Hf 178.49	tantalum 73 Ta 180.95	tungsten 74 W 183.84	rhenium 75 Re 186.21	osmium 76 Os 190.23	iridium 77 Ir 192.22	platinum 78 Pt 195.08	gold 79 Au 196.97	mercury 80 Hg 200.59	thallium 81 Tl 204.38	lead 82 Pb 207.2	bismuth 83 Bi 208.98	polonium 84 Po [209]	astatine 85 At [210]	radon 86 Rn [222]												
francium 87 Fr [223]	radium 88 Ra [226]	actinium 89 Ac [227]	rutherfordium 104 Rf [261]	dubnium 105 Db [262]	seaborgium 106 Sg [266]	bohrium 107 Bh [264]	hassium 108 Hs [265]	meitnerium 109 Mt [268]	unnilium 110 Uun [271]	ununium 111 Uuu [272]	ununium 112 Uub [277]		unquadium 114 Uuq [289]																

* Lanthanide series

** Actinide series

lanthanum 57 La 138.91	cerium 58 Ce 140.12	praseodymium 59 Pr 140.91	neodymium 60 Nd 144.24	promethium 61 Pm [145]	samarium 62 Sm 150.36	europium 63 Eu 151.96	gadolinium 64 Gd 157.26	terbium 65 Tb 158.93	dysprosium 66 Dy 162.50	holmium 67 Ho 164.93	erbium 68 Er 167.26	thulium 69 Tm 168.93	ytterbium 70 Yb 173.04
actinium 89 Ac [227]	thorium 90 Th 232.04	protactinium 91 Pa 231.04	uranium 92 U 238.03	neptunium 93 Np [237]	plutonium 94 Pu [244]	americium 95 Am [243]	curium 96 Cm [247]	berkelium 97 Bk [247]	californium 98 Cf [251]	einsteinium 99 Es [252]	fermium 100 Fm [257]	mendeleevium 101 Md [258]	nobelium 102 No [259]