Some Topics in Atomic Physics at Fudan University Spring 2013

Gordon Berry, Physics Department, University of Notre Dame

The first meeting of the class is on Wednesday, 6 March 2013
All Class Meetings will be at the same time
each **Wednesday**, 6 March, 13 March, 20 March, 27 March and 3 April
Time: 1:30 to 4 pm, including two 5 or 10 minute breaks

Week 1: 6 March: Introduction and Dirac theory for a one-electron atom
Week 2: 13 March: Hyperfine structure
Week 3: 20 March: 2- and 3-electron atoms; doubly excited states
Week 4: 27 March: Coherent state decay processes: quantum beats and polarization
Week 5: 3 April: (a) The Wakefield SELF effect (b) Laser traps and quantum computing

Extra topics, probably not covered in any detail:
1 - Extensions of Hartree Fock theory; 2 - Collisions of fast ions in solids 3

All the slides used in the classes, plus the referenced materials, this synopsis and some homework will be openly available at my website: www.nd.edu/~hgberry/berry1.html

Synopsis

Week 1 - Introduction and Dirac theory for a one-electron atom

We start with an introductory discussion looking for student feedback, including a short test to evaluate level of understanding of the students and to find out what the students would most like to work on during the course.
This section will conclude with a brief introduction to the development of Schrodinger's quantum wave equation, and its application to the square well potential; the most important conclusions will be focused on boundary conditions and their application to derive a finite volume quantum wave function.
We introduce the difficulties of finding a relativistically consistent solution to the wave equation, and the need specify at least two-component matrices for the wavefunctions.
The Dirac equation for the hydrogen atom central 1/r potential is solved exactly - the only example for an exact solution of the complete 4-component Dirac equation. We focus specifically on the exact energy values for the electron in a central filed 1/r potential. We then derive the approximate Pauli energies and compare the results with experiment for the hydrogen atom.
We discuss why the experiments of the hydrogenic fine structure disagree with the Dirac theoretical values. The answer is to add the effects of the full theoretical quantum electrodynamic field theory to these results - we discuss these discrepancies and experiments to measure them. The latest work gives full agreement with the complete theory.

Week 2 - Hyperfine structure

We begin with an elementary introduction to hyperfine structure in atoms - due to the higher order electromagnetic interactions between the electrons and the nucleus. The first , and dominating term is due to the magnetic dipole of the nucleus - only nuclei with spin have non-zero magnetic moments. After the short derivation we discuss the resulting patterns of hyperfine structure in spectral lines, both the line separations and the relative intensities; the students will try one example in class.

Next, we will consider, similarly, the interactions with the electric quadrupole moment of the nucleus. This yields small variations in the previously calculated spectral patterns. These variations provide the means to measure the principal components of the nuclear quadrupole moments.

We discuss more recent measurements using doppler-free laser spectroscopy which give enhanced precision results for these electric quadrupole moments.

In the final part of the class, we introduce a comprehensive theory of the interaction of the nucleus with the atomic electrons. This method introduces the students to extended use of the Wigner-Eckart theorem and irreducible tensors in atomic interaction analysis.

We discuss a key experimental measurement of the nuclear octupole moment in cesium, the only octupole moment to ever be measured using hyperfine structure observations. We discuss this and a few other experiments in detail.

All such experiments can succeed with a minimization of the doppler broadening of the spectral lines - the students make estimates of the line broadening so that we can discuss the temperature and velocity constraints needed.

Week 3: 2- and 3-electron atoms, doubly excited states in helium-like and alkali-like atoms and ions

The students will be asked to describe their ideas and understanding about the energy levels and their modes of decay in any two electron system and compare it with helium.We introduce perturbation theory as a simple example to calculate the groundstate energy of the helium atom, and show that further approximations remain far from the experimental value - with 2 to 10% precision. We discuss the symmetry properties of the two electron wavefunctions, introducing spin and the explicit calculations of required for the subsequent perturbations - eg the definition and use of Slater integrals. We introduce and discuss the historic use of variational calculations using parametric wavefunctions, introduced by Hylleraas in 1929 can provide much more accurate results - the advent of electronic computers in the 1950s had their first major successes in generalizing these variational techniques with hundreds of parameters - they gave precision of parts in 10^8, better than existing experiment, making possible later precise tests of relativistic energy changes in two-electron atoms.

Finally in this section, we discuss a modern variational approach, utilizing fourier transforms, which yields precise energies with only three parameters.

We discuss the possibility of exciting both electrons within a two-electron system, and explain the stability and high energy of such states, and their role as possible sources of several technological relevance such as energy storage and use in x-ray lasers.

We give generalizations of these ideas in alkali-like systems, beginning with lithium and the lithium-like ions: such states were discovered in the excitation of fast ions in accelerator based research. Some of these states are metastable and have subsequently been observed in ion traps such as EBIT, and active research in this area is ongoing.

We give two examples of results from very different types of experiments to highlight the properties of these states.

Week 4: Coherent state decay processes: quantum beats and polarization

We begin with a discussion about the various types of accelerators that have been used to provide fast heavy ion beams for atomic physics experiments - this is a brief history of the pat 50 years of the field. We follow with discussions of some of the unique aspects of the experiments that can be done in such machines utilizing geometries with naturally short time resolution in the atom’s own coordinates down to picoseconds, and in good spatial resolutions of fractions of a mm. These conditions have more recently been overtaken partially with the introdcution of high power pulsed lasers.

We then focus on the symmetry aspects of the cylindrical geometry of the excitation system which led naturally to the first observation of high time/space resolution quantum beats. The work leads naturally to the study of fine and hyperfine structures, and of magnetic (Zeeman) and electric (Stark) splittings in high energy resolution. We discuss in detail the first observations of atomic states with non-zero electric dipole moments, a system which is forbidden (by spatial point symmetry) in a stable atom.

We follow with observations of the effects of breaking the cylindrical symmetry of the fast-ion/solid excitation process. This can occur in two significantly different, but related geometries: the first by passing the fast ions through a tilted excitation surface, and second by impinging the fast ions at grazing incidence on a smooth surface. The effects of "English" in thes atomic collisions can readily be studied through the polarization properties of the light emitted from the escaping atoms and ions. We discuss in detail these polarization properties, how to efficiently measure them. We then give examples of the polarization quantum beats observed, and give a theoretical formalism to explain the measurements.

We end up with a brief illustration of the parallel technique of observations of quatum beats through pulsed electron and laser excitation.

Week 5: (a) The Wakefield SELF effect (b) Laser traps and quantum computing;

(a) We introduce the classical theory of energy loss passing through solids, first developed by Bohr in 1948. We discuss more detailed semi-classical energy loss calculations and illustrate several energy loss effects including those found in crystalline materials and observations of the break-up of molecules in passage through thin foils and crystals. Some of these observations and theoretical calculations develop our understanding of the wake field surrounding a fast moving ion as the fundamental part of their electronic energy losses.

We discuss the latest understanding of energy losses occurring in the surface fields in these same geometries- we have christened this as the SELF (the Surface Energy Loss Field) effect.

(b) We use the ideas developed in the previous classes on quantum beat theories, excitation and fine structure to discuss the latest ideas in quantum computing, and in the use of laser traps for precision measurements of time and for producing very stable atomic clocks.

We will give specific examples of the various types of atomic trap now being used in modern atomic physics research, and the use of this technology to produce coherent superpositions of groups (thousands or more) of atoms in Bose-Einstein condensations. Almost all this work has taken place in the past five to ten years and will bring the the Fudan students up to date with the uses and developments of laser trap technology. We will highlight one possible important use for the future - the use of coherent arrays of atoms to produce a realistic quantum computer. Such computers are likely to become the miniature machines of the future, controlling many aspects of technology in our everyday life.