1 Introduction

A historical development of the structure of atoms, nuclei, and subatomic particles not only involves scientific exploration, but the interplay between science, human cognition, and social behavior. However, the rush of modern science generates so much new knowledge, that the teaching of science has no time to focus on these broader issues. I encourage you to spend the extra hours that are required for you to develop an appreciation of how scientific knowledge expands.

This course will cover, at the advanced undergraduate level, a few subjects which I feel contain the basic physics of subatomic structure and its connection to cosmology. The subject is much too broad to cover in depth, so I intend to address a few, more important subjects. I assume that students have completed an undergraduate course in modern physics, including introductory Quantum Mechanics and Relativity. I also assume that students are familiar with linear algebra, differential equations, the mathematics of special functions, and Fourier transforms. No one text covers all the material, so the lecture notes posted on the class website should be used as the basic reference. Samplings of other reference materials are listed in the syllabus and should be used to supplement a topic in more depth.

2 Scientific Methodology

The practice of reductionism, which is really the foundation of the “scientific method”, has probably been the single most important philosophical concept that accounts for the advance of modern science in western civilization. Reductionism assumes that one can reduce a complex system into several simplified components to which can be assigned a finite set of fundamental axioms. The behavior of the system is then understood through the sum of its parts. Thus applying reductionism in this class, we separately study the properties of subatomic particles, implying that a characterization of each particle can then provides an insight to its interactions and to systems of such particles.

3 Particle Interactions

It is somewhat surprising that there are only 4 known interaction types within physical systems. These are the strong, electromagnetic, weak, and gravitational interactions, listed in order of their decreasing strength. All particles interact gravitationally because all particles
have energy (if only in their mass). However, the gravitational interaction hardly matters in subatomic interactions, with perhaps the exception of very dense, massive, and energetic systems. Therefore the gravitational interaction is generally ignored in particle physics with the exception of cosmological systems. The 3 other interactions, along with mass, are assumed to govern the behavior of subatomic particles.

Special relativity is applied in particular to handle kinematics, although intrinsic spin is a relativistic phenomenon. However, it can be handled by an ad hoc addition to a non-relativistic description. General relativity will be briefly introduced when cosmology is discussed.

The use of symmetry is a powerful tool. In modern theories, symmetries help define the particle type and its interactions. The use of symmetry mathematically characterizes particle interactions, and will be introduced through the example of rotations, reflections, and translations. However, geometric symmetry operations can be extended by incorporating non-spatial dimensions into the mathematical framework which characterize a particle. One of the more important mathematical symmetries of this type is "gauge symmetry". Gauge symmetry is used to unify the electromagnetic, weak interactions, and strong interactions. Finally, all symmetries are best understood through the mathematics of group theory.

4 Atomic Units

Any subject has its own language and physics is not an exception. As one begins this study it is important to understand the language of subatomic physics so that one becomes familiar with various terms and concepts. Thus begin with the discussion of an atom.

An atom is composed of a nucleus, which in its most simplest form, is composed of protons and neutrons (nucleons) bound within a small radius. The electrons are bound electromatically at distances much larger than the nuclear dimensions. The size of a nucleon is on the order of a fermi \((1 \text{ fm} = 10^{-15}\text{m})\) and the size of a nuclear radius is a few tens of fermis. Electrons are essentially point particles. (Of course given the uncertainty relation in QM, is not possible to confine a particle to a point.) Atomic electrons are positioned approximately \(10^{-10}\text{m}\) from the nucleus, and bound by the electromagnetic force between the electrons and the nuclear core. Thus the classical atom is mostly space. In any event, the atomic nucleus, which in its simplest description is composed of A nucleons \((Z\text{ protons and } N\text{ neutrons so that }A = Z + N)\), has charge Ze \((e\text{ is the atomic charge})\). In nuclear notation, a particular atom is written as \(\frac{A}{Z}\text{Symbol}_N\) with \text{Symbol} \((\text{the chemical symbol})\) related to the number of electronic charges, \(Z\). Isotopes have the same value of \(Z\) but different values of the neutron number, \(N\). Thus one writes the iron-56 isotope as \(^{56}\text{Fe}_{30}\).
The mass of the proton is $(1.67239 \pm 0.00004 \times 10^{-24})$ gm. The neutron mass is $(1.67470 \pm 0.00004 \times 10^{-24})$ gm. The mass of an atom includes the sum of the proton, neutron, and electron masses, plus the binding energies (negative in this case). It is convenient to define an atomic mass unit, Mu, defined so that the mass of $^{12}$C (6 protons, 6 neutrons, 6 electrons, and binding energy) is exactly 12. In this mass scale, the masses of individual protons and neutrons are 1.007277 Mu and 1.008665 Mu, respectively.

The sum of the masses of 6 protons, 6 neutrons, and 6 electrons is $12.09894$. However, the mass of $^{12}$C is 12 Mu, so that $0.09894$ Mu is due to binding energy which in energy terms is equivalent to $E = mc^2$. Note that electrons obviously bind to an atom through the electrostatic force between the positive protons and negative electrons. On the other hand, protons are confined within the nuclear volume, so there must be another force to overcome the electromagnetic repulsion. This is called the strong force.

One can also measure the mass of a particle in units of its energy. Usually these units are given in terms of millions of electron volts (MeV). One electron volt is the energy a particle with electronic charge, e, obtains when accelerated by an electrostatic potential gradient of 1 volt. This sets the Mu unit as $931.494$ MeV. A nucleus of medium weight, say $^{56}$Fe, has a mass of some $5.2 \times 10^4$ MeV. However, this is an awkward number so nuclear mass is usually given in units of mass excess which is the difference between the atomic mass in Mu and the sum of the masses of the protons, neutrons, and electrons which compose the nucleus. Thus the mass excess of $^{12}$C is zero by the definition of the Mu unit. A proton has a mass excess of
0.00728 Mu or 6.778 MeV, while the mass excess for the neutron is 0.00866 Mu or 8.071 MeV.

As previously discussed, atomic dimensions are of the order $10^{-10}$ cm. Atomic physicists use the angstrom ($10^{-10}$m) as a unit of length, while nuclear physicists use the Fermi ($10^{-15}$). An empirical relation for a nuclear radius is $1.3 A^{1/3}$ fm. Nuclear scattering cross sections are defined in terms of a unit called “barn”. Figure 2 describes how this unit was named. In the early days of nuclear investigations, the probability of an interaction between an incident nucleon with a nuclear target was described geometrically, as illustrated in Figure 3. It was found that the reaction probability could be described by the cross sectional area of the nucleus as obtained from $\sigma = \pi r^2$. This is on the order of $10^{-24}$ cm which is defined as a barn.

Other useful units are given in Table 1.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light Velocity</td>
<td>$c$</td>
<td>$2.99793 \times 10^8$ cm/s</td>
</tr>
<tr>
<td>Avagadro’s Number</td>
<td>$N$</td>
<td>$6.0249 \times 10^{-23}$ molecules/g-mole</td>
</tr>
<tr>
<td>Electronic Charge</td>
<td>$e$</td>
<td>$1.6021 \times 10^{-19}$ Coulomb</td>
</tr>
<tr>
<td>1 MeV</td>
<td>$\text{MeV}$</td>
<td>$1.6021 \times 10^{-6}$ erg</td>
</tr>
<tr>
<td>1 MeV</td>
<td>$\text{MeV}$</td>
<td>$1.0735 \times 10^{-3}$ Mu</td>
</tr>
<tr>
<td>$h$</td>
<td></td>
<td>$6.5817 \times 10^{-22}$ MeV-s</td>
</tr>
<tr>
<td>$h \cdot c$</td>
<td></td>
<td>$1.9732 \times 10^{-11}$ MeV-cm</td>
</tr>
<tr>
<td>Proton Rest Mass</td>
<td>938.26</td>
<td>MeV</td>
</tr>
<tr>
<td>Neutron Rest Mass</td>
<td>939.55</td>
<td>MeV</td>
</tr>
<tr>
<td>Electron Rest Mass</td>
<td>$c$</td>
<td>0.51101 MeV</td>
</tr>
<tr>
<td>Nuclear Magenton</td>
<td>$\mu$</td>
<td>$3.1524 \times 10^{-18}$ MeV/ gauss</td>
</tr>
<tr>
<td>1 Year</td>
<td></td>
<td>$3.15 \times 10^7$ s</td>
</tr>
<tr>
<td>1 Decay Sec</td>
<td>$\text{Bq}$</td>
<td>1 s$^{-1}$</td>
</tr>
<tr>
<td>1 rem</td>
<td></td>
<td>$5.49 \times 10^7$ MeV/g(air)</td>
</tr>
<tr>
<td>Natural Background</td>
<td>100</td>
<td>mr/yr</td>
</tr>
</tbody>
</table>

6 An Example of Nuclear Charge, the Electromagnetic Force, and the equivalence of Mass and Energy

Charge is a characteristic property of an elementary particle, and with the exception of the permanently bound quarks, is quantized in units of the electronic charge, $e$. The Rutherford experiment of 1912 scattered $^4\text{He}$ nuclei (i.e. $\alpha$ particles) from a thin gold foil 4. The result showed that it was necessary to have a central concentration of positive charge in
How the barn was born

Some time in December of 1942, the authors, being hungry and deprived temporarily of domestic cooking, were eating dinner in the cafeteria of the Union Building of Purdue University. With cigarettes and coffee the conversation turned to the topic uppermost in their minds, namely cross sections. In the course of the conversation, it was lamented that there was no name for the unit of cross section of $10^{-24}$ cm$^2$. It was natural to try to remedy this situation.

The tradition of naming a unit after some great man closely associated with the field ran into difficulties since no such person could be brought to mind. Failing in this, the names Oppenheimer and Bethe were tried, since these men had suggested and made possible the work on the problem with which the Purdue project was concerned. The "Oppenheimer" was discarded because of its length, although in retrospect an "Oppy" or "Opple" would seem to be short enough. The "Bethe" was thought to lend itself to confusion because of the widespread use of the Greek letter. Since John Manley was directing the work at Purdue, his name was tried, but the "Manley" was thought to be too long. The "John" was considered, but was discarded because of the use of the term for purposes other than as the name of a person. The rural background of one of the authors then led to the bridging of the gap between the "John" and the "barn". This immediately seemed good and further it was pointed out that a cross section of $10^{-24}$ cm$^2$ for nuclear processes was really as big as a barn. Such was the birth of the "barn".

To the best knowledge of the authors, the first public (if it may be called that) use of the barn was in Report LAMS-2 (28 June, 1943) in which the barn was defined as a cross section of $1 \times 10^{-24}$ cm$^2$.

Editor's note: The above is the full text of Los Alamos report "Note on the Origin of the Term 'barn'," LAMS 523, submitted by the authors 13 September, 1944, issued 5 March, 1947 and declassified 4 August, 1948.

The authors would like to insist that the "barn" is spelled just that way, that no capital letter "b" is needed, and that the plural is "barns" with no letter "e" involved, and that the symbol be a small "b." The meanings of "milli-barn" and "kilobarn" are obvious.

M. G. Holloway
C. P. Baker
Los Alamos, 1944

Figure 2: A short narrative describing how the 'unit, 'barn'', was named
Figure 3: A simple description of a nuclear scattering cross section. Note this assumes “black body” interactions which means the nucleus completely absorbs the incident particle.

Figure 4: A schematic of scattering showing the connection of the scattering angle to the impact parameter.

A volume with radius on the order of $10^{-15}$m. A hitherto unknown force was required to hold the protons within the nuclear volume. This force acts between the nucleons, having an interaction range of nuclear dimensions. Although weaker than the nuclear force, the Coulomb force acts over a much longer range. Thus nuclear physics is the study of the multi-particle, hadronic (strong) interaction.

If the nuclear charge is spread evenly over a spherical volume, the potential energy due to the repulsive force of the positive charge is:

$$U = (1/2) \int dv \phi \rho,$$

where $\phi$ is the electric potential and $\rho$ is the charge density of the nucleus. The integral is over the nuclear volume. The electronic potential is:

$$\phi = \frac{Ze}{r_0} [\frac{3}{2} - \frac{1}{2} (r/r_0)] \quad r < r_0,$$

and the charge density is given by:

$$\rho = \frac{Ze}{4/3 \pi r^2}.$$
Upon integration the potential energy stored in a nucleus is:

\[ U = \frac{3}{5} \left( \frac{ds (Ze)^2}{r_0} \right) \]

Actually the factor “\(Z^2\)” should be replaced by “\(Z(Z-1)\)” to remove the self-interaction of the discrete charges. Thus a Uranium nucleus with a radius of 8 fm has a stored potential energy of approximately:

\[ U^{(235U)} = \left( \frac{3}{5} \right)(92)(91)(1.44/8) = 904 \text{ MeV} \]

Now suppose the Uranium atom fissions producing 2 nuclei with \(A_1 + A_2 = A\) plus 2 neutrons. Then for example if \(A_1 = A_2 = A/2\):

\[ \Delta U = 904 - 2(284) = 336 \text{ MeV} \]

The mass difference results in the energy is released when the nucleus fissions.

Nuclear fission or fusion can release energy due to binding energies of the participating nuclei as observed in the masses of the constituents. A plot of binding energy per atomic number vs atomic number, \(A\), is shown in Figure 5.