CONTENT BEYOND SYLLABUS

NUCLEAR PHYSICS

Nuclear physics is the field of physics that studies atomic nuclei and their constituents and interactions. The most commonly known application is nuclear power generation, but the research has led to applications in many fields, including nuclear medicine and magnetic resonance imaging, nuclear weapons, ion implantation in materials engineering, and radiocarbon dating in geology and archaeology.

The field of particle physics evolved out of nuclear physics and is typically taught in close association with nuclear physics.

The history of nuclear physics as a discipline distinct from atomic physics starts with the discovery of radioactivity by Henri Becquerel in 1896, while investigating phosphorescence in uranium salts. The discovery of the electron by J. J. Thomson a year later was an indication that the atom had internal structure. At the beginning of the 20th century the accepted model of the atom was J. J. Thomson's "plum pudding" model in which the atom was a positively charged ball with smaller negatively charged electrons embedded inside it.

Radioactivity was extensively investigated, notably by the husband and wife team of Pierre Curie and Marie Curie and by Ernest Rutherford and his collaborators. By the turn of the century physicists had also discovered three types of radiation emanating from atoms, which they named alpha, beta, and gamma radiation. Experiments by Otto Hahn in 1911 and by James Chadwick in 1914 discovered that the beta decay spectrum was continuous rather than discrete. That is, electrons were ejected from the atom with a continuous range of energies, rather than the discrete amounts of energy that were observed in gamma and alpha decays.

The discovery, with Rutherford's analysis of the data in 1911, led to the Rutherford model of the atom, in which the atom had a very small, very dense nucleus containing most of its mass, and consisting of heavy positively charged particles with embedded electrons in order to balance out the charge (since the neutron was unknown). As an example, in this model (which is not the modern one) nitrogen-14 consisted of a nucleus with 14 protons and 7 electrons (21 total particles) and the nucleus was surrounded by 7 more orbiting electrons.

The Rutherford model worked quite well until studies of nuclear spin were carried out by Franco Rasetti at the California Institute of Technology in 1929. By 1925 it was known that protons and electrons each had a spin of $\frac{1}{2}$. In the Rutherford model of nitrogen-14, 20 of the total 21 nuclear particles should have paired up to cancel each other's spin, and the final odd particle should have left the nucleus with a net spin of $\frac{1}{2}$. Rasetti discovered, however, that nitrogen-14 had a spin of 1.

With the discovery of the neutron, scientists could at last calculate what fraction of binding energy each nucleus had, by comparing the nuclear mass with that of the protons and neutrons which composed it. Differences between nuclear masses were calculated in this way. When nuclear reactions were measured, these were found to agree with Einstein's calculation of the equivalence of mass and energy to within 1% as of 1934.

Nuclear decay

Eighty elements have at least one stable isotope which is never observed to decay, amounting to a total of about 254 stable isotopes. However, thousands of isotopes have been characterized as unstable. These "radioisotopes" decay over time scales ranging from fractions of a second to trillions of years.

The most stable nuclei fall within certain ranges or balances of composition of neutrons and protons: too few or too many neutrons (in relation to the number of protons) will cause it to decay. For example, in beta decay a nitrogen-16 atom (7 protons, 9 neutrons) is converted to an oxygen-16 atom (8 protons, 8 neutrons)[19] within a few seconds of being created. In this decay a neutron in the nitrogen nucleus is converted by the weak interaction into a proton, an electron and an antineutrino. The element is transmuted to another element, with a different number of protons.

In alpha decay, the radioactive element decays by emitting a helium nucleus (2 protons and 2 neutrons), giving another element, plus helium-4. In many cases this process continues through several steps of this kind, including other types of decays (usually beta decay) until a stable element is formed.In gamma decay, a nucleus decays from an excited state into a lower energy state, by emitting a gamma ray. The element is not changed to another element in the process (no nuclear transmutation is involved).

Nuclear fusion

In nuclear fusion, two low mass nuclei come into very close contact with each other, so that the strong force fuses them. It requires a large amount of energy for the strong or nuclear forces to overcome the electrical repulsion between the nuclei in order to fuse them; therefore nuclear fusion can only take place at very high temperatures or high pressures. When nucelei fuse, a very large amount of energy is released and the combined nucleus assumes a lower energy level. The binding energy per nucleon increases with mass number up to nickel-62. Stars like the Sun are powered by the fusion of four protons into a helium nucleus, two positrons, and two neutrinos. The uncontrolled fusion of hydrogen into helium is known as thermonuclear runaway.

Nuclear fission

Nuclear fission is the reverse process to fusion. For nuclei heavier than nickel-62 the binding energy per nucleon decreases with the mass number. It is therefore possible for energy to be released if a heavy nucleus breaks apart into two lighter ones.

Chain reactions were known in chemistry before physics, and in fact many familiar processes like fires and chemical explosions are chemical chain reactions. The fission or "nuclear" chain-reaction is the source of energy for nuclear power plants and fission type nuclear bombs, Heavy nuclei such as uranium and thorium may also undergo spontaneous fission, but they are much more likely to undergo decay by alpha decay.

PIEZOELECTRIC EFFECT

The nature of the piezoelectric effect is closely related to electric dipole moments in solids. It may either be induced for ions on crystal lattice or may be carried by molecular groups. The dipole density or polarization may be calculated for crystals by summing up the dipole moments per volume of the crystallographic unit cell. As every dipole is a vector, the dipole density ***P*** is a vector field. Dipoles near each other tend to be aligned in regions called Weiss domains. The piezoelectric effect is the change of polarization ***P*** when applying a mechanical stress.. Piezoelectricity may then manifest in a variation of the polarization strength, its direction or both, with the details depending on: 1. the orientation of ***P*** within the crystal; 2. crystal symmetry; and 3. the applied mechanical stress.

What Is the Piezoelectric Effect?

The *piezoelectric effect* refers to a change in electric polarization that is produced in certain materials when they are subjected to mechanical stresses. This stress-dependent change in polarization manifests as a measurable potential difference across the material. An important feature to note about this phenomenon is that the process is reversible. The *inverse piezoelectric effect* refers to a deformation of these materials that results from the application of an electric field. The deformation could lead to either tensile or compressive strains and stresses in the material depending upon the direction of the electric field, the preferred direction of polarization in the material, and how the material is connected to other adjacent structures.

Areas of Application

Actuators and Sensors

Piezoelectric materials are widely used in compact actuators such as linear motors, rotary motors, and pumps. They are also used in sensors such as load cells, pressure sensors, accelerometers, and gyroscopes. Novel actuator and sensor designs could involve composites with embedded piezoelectric materials that display coupled structural deformation in different modes such as in a *shear-bender,* where a shear deformation of the embedded piezoelectric material produces a largely bending deformation of the composite structure.

Acoustics

Acoustic transducers use piezoelectric materials to generate sound waves. When subjected to a harmonically varying electric field, a vibrating piezoelectric material creates alternate compression and rarefaction in the surrounding fluid media, which results in the production of sound. This principle is used in miniature speakers in portable electronic devices, medical ultrasound devices, and SONAR transducers, such as the tonpilz transducer. The direct piezoelectric effect allows piezoelectric materials to be used for acoustic sensing, for example, in microphones, hydrophones, and even pick-ups for acoustic-electric guitars. In these devices, the external sound pressure acts like a mechanical load on the piezoelectric material, thereby changing its electrical response, which can be measured and correlated with the acoustic signal.

WAVE OPTICS

The interaction of light waves with matter and its practical applications to optical devices like mirrors. light is an electromagnetic wave.Wave optics is a broad subject, but this example will help us to pick out a reasonable set of restrictions to make things more manageable:

(1) A wave travels through a uniform medium, encounters a certain area in which the medium has different properties, and then emerges on the other side into a second uniform region.

(2) We assume that the incoming wave is a nice tidy sine-wave pattern with wave fronts that are lines (or, in three dimensions, planes).

The simpler wave patterns that occur farther away, so that the main question of interest is how intense the outgoing wave is at a given angle.The kind of phenomenon described by restriction is called *diffraction*. Diffraction can be defined as the behavior of a wave when it encounters an obstacle or a non uniformity in its medium. In general, diffraction causes a wave to bend around obstacles and make patterns of strong and weak waves radiating out beyond the obstacle. Understanding diffraction is the central problem of wave optics.

Diffraction can be used to find the structure of an unknown diffracting object: even if the object is too small to study with ordinary imaging, it may be possible to work backward from the diffraction pattern to learn about the object. The structure of a crystal can be determined from its x-ray diffraction pattern.

The correspondence principle

Wave optics is a more general theory than ray optics, so in any case where ray optics is valid, the two theories will agree. This is an example of a general idea enunciated by the physicist Niels Bohr, called the *correspondence principle:*

“when flaws in a physical theory lead to the creation of a new and more general theory, the new theory must still agree with the old theory within its more restricted area of applicability. After all, a theory is only created as a way of describing experimental observations. If the original theory had not worked in any cases at all, it would never have become accepted.”

Huygens' principle

The example of double-slit diffraction, note the strong visual impression of two overlapping sets of concentric semicircles. This is an example of *Huygens' principle*, named after a Dutch physicist and astronomer. Huygens' principle states that any wave front can be broken down into many small side-by-side wave peaks, which then spread out as circular ripples, h, and by the principle of superposition, the result of adding up these sets of ripples must give the same result as allowing the wave to propagate forward, i. In the case of sound or light waves, which propagate in three dimensions, the “ripples” are actually spherical rather than circular, but we can often imagine things in two dimensions for simplicity.

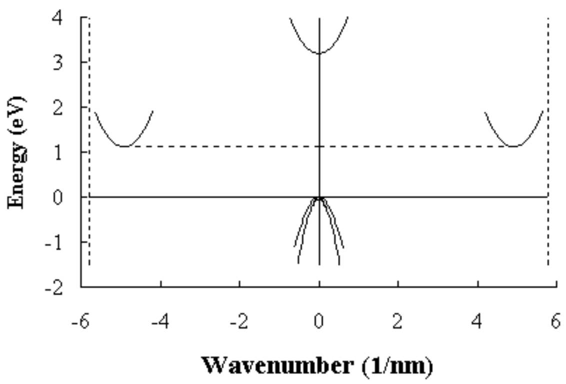
In double-slit diffraction the application of Huygens' principle is visually convincing: it is as though all the sets of ripples have been blocked except for two.Huygens ‘Principle gives the right results in the case of an unobstructed linear wave, h and i. A theoretically infinite number of circular wave patterns conspire to add together and produce the simple linear wave motion with which we are familiar.

Since Huygens ‘Principle is equivalent to the principle of superposition, and superposition is a property of waves, what Huygens had created was essentially the first wave theory of light. Isaac Newton loved the atomic theory of matter so much that he searched enthusiastically for evidence that light was also made of tiny particles. The paths of his light particles would correspond to rays in our description; the only significant difference between a ray model and a particle model of light would occur if one could isolate individual particles and show that light had a “graininess” to it. Newton never did this, so although he thought of his model as a particle model, it is more accurate to say he was one of the builders of the ray model.

Almost all that was known about reflection and refraction of light could be interpreted equally well in terms of a particle model or a wave model, but Newton had one reason for strongly opposing Huygens' wave theory. Newton knew that waves exhibited diffraction, but diffraction of light is difficult to observe, so Newton believed that light did not exhibit diffraction, and therefore must not be a wave. Although Newton's criticisms were fair enough, the debate also took on the overtones of a nationalistic dispute between England and continental Europe, fueled by English resentment over Leibniz's supposed plagiarism of Newton's calculus. Newton wrote a book on optics, and his prestige and political prominence tended to discourage questioning of his model.

EFFECTIVE MASS OF ELECTRON

The effective mass of a semiconductor is obtained by fitting the actual *E-k* diagram around the conduction band minimum or the valence band maximum by a parabola. While this concept is simple enough the issue turns out to be substancially more complex due to the multitude and the occasional anisotropy of the minima and maxima. In this section we first describe the different relevant band minima and maxima, present the numeric values for germanium, silicon and gallium arsenide and introduce the effective mass for density of states calculations and the effective mass for conductivity calculations.



The above figure Shown is the *E-k* diagram within the first brillouin zone and along the (100) direction. The energy is chosen to be to zero at the edge of the valence band. The lowest band minimum at $k = 0$ and still above the valence band edge occurs at $E_{c,direct} = 3.2$ eV. This is not the lowest minimum above the valence band edge since there are also 6 equivalent minima at k = (x,0,0), (-x,0,0), (0,x,0), (0,-x,0), (0,0,x), and (0,0,-x) with x = 5 nm^{-1}. The minimum energy of all these minima equals 1.12 eV = $E_{c,indirect}$. The effective mass of these anisotropic minima is characterized by a longitudinal mass along the corresponding equivalent (100) direction and two transverse masses in the plane perpendicular to the longitudinal direction. In silicon the longitudinal electron mass is $m_{e,l}^* = 0.98\ m_0$ and the transverse electron masses are $m_{e,t}^* = 0.19\ m_0$, where $m_0 = 9.11 \times 10^{-31}$ kg is the free electron rest mass.Two of the three band maxima occur at 0 eV. These bands are refered to as the light and heavy hole bands with a light hole mass of $m_{lh}^* = 0.16\ m_0$ and a heavy hole mass of $m_{hh}^* = 0.46\ m_0$. In addition there is a split-off hole band with its maximum at $E_{v,so} = -0.044$ eV and a split-off hole mass of $m_{v,so}^* = 0.29\ m_0$.
The effective mass for conductivity calculation is the mass which is used in conduction related problems accounting for the detailed structure of the semiconductor. These calculations include mobility and diffusion constants calculations. Another example is the calculation of the shallow impurity levels using a hydrogen-like model.

As the conductivity of a material is inversionally proportional to the effective masses, one finds that the conductivity due to multiple band maxima or minima is proportional to the sum of the inverse of the individual masses, multiplied by the density of carriers in each band, as each maximum or minimum adds to the overall conductivity. For anisotropic minima containing one longitudinal and two transverse effective masses one has to sum over the effective masses in the different minima along the equivalent directions.

JOSEPHSON EFFECT AND ITS APPLICATION

The Josephson effect is the phenomenon of super current —i.e. a current that flows indefinitely long without any voltage applied—across a device known as a Josephson junction (JJ), which consists of two superconductors coupled by a weak link. The weak link can consist of a thin insulating barrier (known as a superconductor–insulator–superconductor junction, or S-I-S), a short section of non-superconducting metal (S-N-S), or a physical constriction that weakens the superconductivity at the point of contact (S-s-S).

Two superconductors separated by a thin insulating layer can experience tunneling of Cooper pairs of electrons through the junction. The Cooper pairs on each side of the junction can be represented by a wave function similar to a free particle wave function. In the DC Josephson effect, a current proportional to the phase difference of the wave functions can flow in the junction in the absence of a voltage. In the AC Josephson effect, a Josephson junction will oscillate with a characteristic frequency which is proportional to the voltage across the junction. The Josephson Effect is an example of a macroscopic quantum phenomenon. The DC Josephson effect had been attributed to "super-shorts" or breaches in the insulating barrier leading to the direct conduction of electrons between the superconductors. The first paper to claim the discovery of Josephson's effect, and to make the requisite Devices based upon the characteristics of a Josephson junction are valuable in high speed circuits. Josephson junctions can be designed to switch in times of a few picoseconds. Their low power dissipation makes them useful in high-density computer circuits where resistive heating limits the applicability of conventional switches.

The superconducting quantum interference device (SQUID) consists of two superconductors separated by thin insulating layers to form two parallel Josephson junctions. The device may be configured as a magnetometer to detect incredibly small magnetic fields -- small enough to measure the magnetic fields in living organisms. Squids have been used to measure the magnetic fields in mouse brains to test whether there might be enough magnetism to attribute their navigational ability to an internal compass.

Superconducting transistors based on Josephson junctions could be used to switch voltages very quickly without the current requirements for power that exist in the present computer design. These devices offer the potential to significantly speed up the processing of signals. This is critical in the Internet age. In such devices, a current of a particular size will flow across the insulator barrier in a Josephson junction with no voltage between the superconductors on either side of the barrier. The current remains at practically zero for increasing low voltages across the barrier until another threshold voltage is achieved, whereupon the current rises to the zero voltage level and then continues to climb almost linearly from there. This enables the Josephson junction to act as a transistor of extraordinary speed. Superconductive films could result in more densely packed chips that transmit information more rapidly by several orders of magnitude. These could be used in supercomputers.

HARTLEY OSCILLATOR

The Hartley oscillator is distinguished by a tank circuit consisting of two series-connected coils (or, often, a tapped coil) in parallel with a capacitor, with an amplifier between the relatively high impedance across the entire LC tank and the relatively low voltage/high current point between the coils. The original 1915 version used a triode as the amplifying device in common plate (cathode follower) configuration, with three batteries, and separate adjustable coils. The simplified circuit shown to the right uses a JFET (in common-drain configuration), an LC tank circuit (here the single winding is tapped) and a single battery. The circuit illustrates the Hartley oscillator operation:[

- the output from the JFET's *source* (*emitter*, if a BJT had been used; *cathode* for a triode) has the same phase as the signal at its gate (or base) and roughly the same voltage as its input (which is the voltage across the entire tank circuit), but the *current is amplified*, i.e. it is acting as a current buffer or voltage-controlled voltage-source.
- this low impedance output is then fed into the coil tapping, effectively into an autotransformer that will step up the voltage, requiring a relatively high current (compared with that available at the top of the coil).
- with the capacitor-coil resonance, all frequencies other than the tuned frequency will tend to be absorbed (the tank will appear as nearly 0Ω near DC due to the inductor's low reactance at low frequencies, and low again at very high frequencies due to the capacitor); they will also shift the phase of the feedback from the 0° needed for oscillation at all but the tuned frequency.

Variations on the simple circuit often include ways to automatically reduce the amplifier gain to maintain a constant output voltage at a level below overload; the simple circuit above will limit the output voltage due to the gate conducting on positive peaks, effectively damping oscillations A quite different implementation using a tapped coil in an LC tank feedback arrangement is to employ a common-grid (or common-gate or common-base) amplifier stage, which is still non-inverting but provides *voltage gain* instead of *current gain*; the coil tapping is still connected to the cathode (or source or emitter), but this is now the (low impedance) input to the amplifier; the split tank circuit is now dropping the impedance from the relatively high output impedance of the plate (or drain or collector).

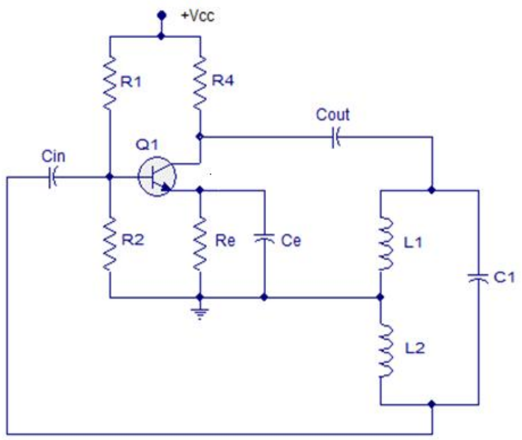
The Hartley oscillator is the dual of the Colpitts oscillator which uses a voltage divider made of two capacitors rather than two inductors. Although there is no requirement for there to be mutual coupling between the two coil segments, the circuit is usually implemented using a tapped coil, with the feedback taken from the tap, as shown here. The optimal tapping point (or ratio of coil inductances) depends on the amplifying device used, which may be a bipolar junction transistor, FET, triode, or amplifier of almost any type (non-inverting in this case, although variations of the circuit with an earthed centre-point and feedback from an inverting amplifier or the collector/drain of a transistor are also common), but a junction FET (shown) or triode is often employed as a good degree of amplitude stability (and thus distortion reduction) can be achieved with a simple grid leak resistor-capacitor combination in series with the gate or grid (see the Scott circuit below) thanks to diode conduction on signal peaks building up enough negative bias to limit amplification.

The frequency of oscillation is approximately the resonant frequency of the tank circuit. If the capacitance of the tank capacitor is C and the total inductance of the tapped coil is L then

$$f = \frac{1}{2\pi\sqrt{LC}}$$

If two *uncoupled* coils of inductance L_1 and L_2 are used then

$$L = L_1 + L_2$$



Hartley oscillator