DEPARTMENT OF PHYSICS AND TECHNOLOGY

Master Thesis in Medical Physics

Neutron Imaging with ALPIDE chips

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2.1 Neutron Interactions

A neutron constitute three quarks (udd). The up (u) and down (d) quarks have charge (u: +2/3e, d: -1/3e) and mass. Together they provide the neutron with mass, energy and net charge equal to zero. Because of its intrinsic properties, a neutron is subject to three of the four fundamental forces; weak, strong and gravitational. Due to the lack of charge neutrons do not interact electromagnetically. Like all particles with mass and energy, the neutron is affected by gravity. The weak and strong nuclear force operate between quarks and are thus relevant when considering neutrons. The strong force is responsible for holding quarks together, to form nucleons, as well as binding protons and neutrons, to form atomic nuclei. The weak force is liable for fusion reactions as well as radioactive decay of atoms. It is also the driving force of free decaying neutrons, with a lifetime of 15 min. Its force carrier, the W boson, is quite heavy. Because of this the weak interaction typically occurs much slower than other interactions. This is why the free neutron has such a long lifetime in comparison to particles prone to other decay forces (e.g. electromagnetically-decaying pions have lifetime 10^{-16}s). Nuclear forces operate only when interacting particles are extremely close to one another, the strong force at 10^{-15}cm and the weak force closer still at 10^{-18}cm. These distances are considerably small compared to the infinite range of gravity. Though the gravitational range is large, its strength relative to the strong force is negligible. Strength of the strong force also outweighs the weak, by factor 10^6. (source? Wiki...)

A neutron may interact with matter in one of five ways:

1. Elastic scattering
2. Inelastic scattering
3. Neutron capture
4. Nuclear spallation
5. Nuclear fission

2.1.1 Elastic Scattering

In particle physics, scattering refers to a particle collision which deflects the particle trajectories. After scattering the particles propagate in a different direction than before. For the process to be classified as elastic scattering the systems total kinetic energy and momentum (in the laboratory frame of reference) must be conserved. Fig ?? illustrates a neutron on a path colliding with a target nucleus at rest. The neutron has kinetic energy E_N and is heading towards the nucleus of atomic number A. During collision, kinetic energy is transferred from the

neutron to the target. Elastic collisions conserve kinetic energy, energy lost by the projectile is gained by the target. After collision the recoil nucleus has energy E_R and propagates to initial path. Recoil target gains kinetic energy $\Delta E = E_N - E_R$ and is scattered ϕ. Angles of final trajectories must conserve momentum. Using classical momentum and kinetic energy equations, combined with a little math, maximum nucleus recoil energy can be expressed as

$$E_R = E_N \left(\frac{A-1}{A+1} \right)^2 \tag{2.1}$$

and maximum energy transfer as

$$\frac{\Delta E}{E_N} = 1 - \left(\frac{A-1}{A+1} \right)^2 \tag{2.2}$$

From equation 2.2 it is apparent that maximum recoil energy is highest for nuclear targets of low atomic weight.

2.1.2 Inelastic Scattering

Similar to elastic scattering, inelastic scattering results in deflection of neutron trajectory and a recoil nucleus. In inelastic scattering, the target nucleus absorbs and reemits the neutron. In the process some kinetic energy is converted into nuclear excitation. Neutron absorption raises the nucleus to an excited energy state. The nucleus emits one or more gamma rays until it becomes stable. Angular momentum is conserved, however, kinetic energy is not.

2.1.3 Neutron Capture

In neutron capture an incident neutron is absorbed by the target nucleus. Nuclear atomic number increases upon absoption by one unit and consequencly undergoes nuclear compound formation. The resultant compound nucleus is either stable or unstable. The latter leads to emission of nuclear radiation, heavy ion and/or other fundamental particles. (source? Wiki?) There are two categories of neutron capture, radiative and nonradiative. Radiative capture reactions produce an excited compound nucleus prone to de-excitation via gamma decay; one or more gamma rays are emitted until the nucleus reaches ground state. On the other hand, nonradiative capture reactions produce a daughter nucleus accompanied by more than one neutron (since single neutrons emission reactions are considered as inelastic scattering) or charged particles like protons and alphas. Some of the significant capture reactions for neutron detection are B-10(n,a)Li*, Li-7(n,a)H-3 and He-3(n,p)H. Reaction equations and nomenclature of capture reactions are listed in Table ??.

The importance of capture reactions are discussed in subsection ?? and an in-depth discussion of gadolinium neutron capture is provided in subsection ??.

2.1.4 Nuclear Spallation

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2.1.5 Nuclear Fission

Neutron induced fission is a nuclear reaction (or nuclear decay process) in which an atom absorbs a neutron and splits into two or more fission fragments. In contrast to nonradiative capture where reaction products are a heavy ion accompanied by smaller particles, fission products are comparable in size, though slightly different. Some reactions also produce neutrons which can contribute to self-sustainable fission chains. Fission reactions release a tremendous amount of energy compared to other neutron reactions. Because of this they provide an effective method for detector neutrons, especially in high gamma environments, which becomes apparent in later chapters.

2.2 Charged Particle Interactions

Particles with electrical charge are subject to electromagnetic forces. Matter is made up of atoms, which composite atomic electrons and nuclei. Atomic constituents are each surrounded by an electric field and in the path of a traversing particle, causes deacceleration and divergence from its original trajectory. Energy loss mechanisms of a charged particle are:

- Elastic collision with atomic nuclei
- Elastic scattering with atomic electrons
- Inelastic scattering with atomic electrons
- Cherenkov
- Transition radiation
- Bremsstrahlung

Again, one must distinguish based on particle properties, this time, namely mass. The mass of a "heavy" particle is one atomic unit or greater. This includes protons, alpha and other ions. That leaves electrons and positrons as "light" particles, with an atomic mass is ... Less than protons. Heavy particles (e.g. ions) are less effected by a nuclei electric field than light particles (e.g. electrons). Elastic scattering of the nuclei effect both heavy and light, however, the impact is greater for the latter.

2.2.1 Heavy charged particles and Bethe-Bloch

Though there are several types of interactions, heavy charged particles mainly lose energy due to inelastic collisions with outer-shell electrons. The Bethe-Bloch formula describes their average energy loss per unit length:

$$-\frac{dE}{dx} = K\rho\frac{Z}{A}\frac{z^2}{\beta^2}\left[\ln\frac{2m_ec^2\beta^2\gamma^2T_{max}}{I^2} - 2\beta^2 - \delta - 2\frac{C}{Z}\right] \tag{2.3}$$

where:

$$K = 2\pi N_a {r_e}^2 m_e c^2 = 0.1535 MeV cm^2/g \tag{2.4}$$

r_e:	classical electron radius = $2.817 \times 10^{-}13 cm^2/g$	ρ:	density of absorbing material
m_e:	electron mass	z:	charge of incident particle in unit of e
N_a:	Avogadro's number = $6.022 \times 10^{23} mol^{-1}$	β =	p/c of the incident particle
		γ =	$1/\sqrt{1-\beta^2}$
I:	mean excitation potential	δ:	density correction
Z:	atomic number of absorbing material	C:	shell correction
		W_{max}:	maximum energy transfer in a single collision
A:	atomic weight of absorbing material		

Noteworthy symbols in the formula are β (representative of incident particle speed) and z (charge of incident particle). According to bethe-bloch, $\beta = v/c$, and thus mean energy loss dE/dx, is inversely proportional to v^2, the particle speed squared. As particles slow down their speed decreases and energy deposition increases, until fully at rest. The other dependency z shows how particles of heavier charge ionize material more effectively. (rewrite)

2.2.2 Electrons

Light particles lose energy via other interactions in addition to elastic scattering. The total energy loss is a combination of radiational and collisional loss.

$$\left(\frac{dE}{dx}\right)_{tot} = \left(\frac{dE}{dx}\right)_{col} + \left(\frac{dE}{dx}\right)_{rad} \tag{2.5}$$

Collisional loss can be described by modifying Bethe-Bloch. Light particles are small in mass, as per definition, and are prone to scattering. Like heavy particles, workings of collision also apply for light particles. However, Bethe-Bloch's assumptions of large incident particle mass and non-deviating trajectory are no longer valid and must be corrected for. Moreover, in case of an incident electron, collisions occur with identical particles, atomic electrons, and the formula must account for their indistinguishability. This changes a couple of terms in Bethe-Bloch, notably maximum allowed energy transfer $W_max = \frac{T_e}{2}$ for electrons of kinetic energy T_e. Considering electron properties, the modified formula becomes

$$-\frac{dE}{dx} = K\rho\frac{Z}{A}\frac{1}{\beta^2}\left[\ln\frac{\tau^2(\tau+2)}{2(I/m_eC^2)^2} + F(\tau) - \delta - 2\frac{C}{Z}\right] \tag{2.6}$$

The particles kinetic energy is represented by t, in units of mc^2 and, for electrons,

$$F(\tau) = 1 - \beta^2 + \frac{\frac{\tau^2}{8} - (2r+r)\ln 2}{(\tau+1)^2} \tag{2.7}$$

Light particles also lose energy by radiation. Electrons passing a nucleus experience an attractive coulomb force exerted by the nucleus positive electric field. In a curved like manner, the electrons deviate from their straight-line path and accelerate. Accelerating charged particles emit electromagnetic waves known as breaking radiation, or bremsstrahlung. Bremsstrahlung comes at a cost of diminishing particle kinetic energy. In other words, scattered electrons slow down.

An electron can lose up to 100% of its energy in only one or two photons. Because of this, same energy electrons vary greatly in energy loss and path length.

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Other interactions... Range ...

2.3 Photon Interactions

In matter, there many processes in which photons may partake. In radiaiton detection the three most important are photoelectric absorption, Compton scattering and pair production. These processes result in photon absorption and/or scattering.

2.3.1 Photoelectric Absorption

The process of photoelectric absorption involves a photon and an atomic electron. Upon collision the photon is absorbed, and a photoelectron is emitted from the atom. Energy of the disappearing photon is transferred to the electron as kinetic energy and equals $E_{gamma} - E_{bi,m}$ where $E_{bi,m}$ is the binding energy of the photoelectrons original shell. Emission of inner shell electrons (e.g. from K-shell) are most probable. A vacancy appears in one of the atoms bound shells. This vacancy if filled by free electrons or electrons from other atomic shells. Electron rearrangement in the atom results in x-ray emission. An electron descending from atomic shell m to n is mediated by an x-ray photon of energy

$$E_{XR} = E_{bi,m} - E_{bi,n} \tag{2.8}$$

where $E_{bi,n}$ represents original binding energy the descending electron. As can be seen in fig??, photoelectric absorption probability decreases with increasing energy. It is the most likely interaction for photons less energetic than 1 MeV. It also depends on atomic number and occurs more frequent in high Z-materials.

2.3.2 Compton Scattering

Another way photons may interact is with free or loosely bound atomic electrons. This process is called compton scattering. Compton, because it was discoved by Arthur Compton and "scattering" because particle trajectories (?) are altered. In the shadow of the speed of EM waves, electron speed is assumed to be negligeble and equal to zero. From the electrons frame of reference the incomming photon has energy E_{gamma}. Once in close proximity (?) the photon and electron interacts through (?). During the interaction, energy is transfered from the photon to the electron. The interaction must occur in such a way that laws of convservation are conserved. Energy gained by the electron must equal energy lost by the photon. Also, final particle trajectories must conserve momentum. Assuming the photon travels along a horizontal line and the electron is at rest, the systems initial momentum is represented by the photons inital energy and direction. The net momentum vector, both before and after collision, is parallel to the horizon and has no vertical component. Thus the scattered particles must travel vertially in opposite directions, but in the same horizontal direction as the initial photon. The scattered trajectory angles must be such that the vertical components add to zero and horizontal components equals initial momentum. Compton scatter occur in the energy range $10^2 eV$ to 100GeV and is the most probable interaction for photons in proximity of $10^4 eV$.

2.3.3 Pair Production

pair production requires considerably higher photon energies than the aforementioned. The concept behind pair production is the creation of anti-particles. A highly energetic photon can

decay(?) into a particle pair in which the particles are the anti-particle of the other. The lowest energy required is 1.022 MeV. Decay of such a photon results in an electron-positron pair. The pair contributes to charge conservation (net charge is zero) as well as conservation of energy and momentum. Rest energy of electrons/positrons is 1.022/2. Hence a minimum of 1.022 MeV is required for the production. Excess energy beyond this value is gained by the particles as kinetic energy. For higher energies other anti-particle pairs may also be produced, such as muon-antimuon or proton-antiproton [wiki].

2.3.4 Beam Attenuation

The following scenario is illustrated in figure ??. A collimated photon beam of intensity I is directed at an absorbing target material. The beam consists of many individual photons travelling parallel to each other. Some of the photons interact with matter and are either deflected or absorbed. An absorbed photon disappears completely. Deflected photons diverge from their original path, usually at a notable deflection angle. As the beam penetrates the target, constituent photons are removed and beam intensity decreases.

Like most radiation, gamma attenuation can be modeled by Beer-Lamberts law

$$I = I_0 e^{-t} \tag{2.9}$$

where I is transmitted beam intensity after traversing an absorber of thickness t. It is also dependent on the attenuation coefficient μ of the target, which in turn depends on the target's density.

Chapter 3

Neutron Detection Principles

3.1 Neutron Conversion

3.2 Radiation Detectors

Chapter 4

Gadolinium-Neutron Capture

Gadolinium (Gd) is a chemical element with atomic number 64. It is a metal and appears as a solid under standard pressure and room temperature. In nature Gd occurs as a composition of seven isotopes; the most abundant being Gd-158 (24.84%), followed by Gd-160 (21.86%), Gd-156 (20.47%), Gd-157 (15.67%) and Gd-157 (14.80%).

Gd has many favorable characteristics allowing an eclectic range of use; for instance in alloys to make magnets, electronics and data storage disks(*); and as a contrast agent in MRI, to diagnose cancerous tumors(*). Of particular interest is its high neutron absorption cross section, high probability of neutron capture. Of all known natural occurring nuclei, Gd-157 has the highest neutron absorption cross section having resonance at thermal-neutron energies (*). As efficient neutron absorbers, Gd plays an important role in neutron shielding alloys for nuclear reactor safety and storage (*). An additional use of great Gd neutron capture is as Gd-based neutron poison, for instance Gd(III) nitrate in moderator systems for regulating power generation and shut-down of Heavy Water Nuclear Reactors (* page 31). Not limited to the field of nuclear physics, Gd neutron absorption capability also benefit(s?) neutron capture therapy for cancer treatment and neutron detection, due to reaction products following neutron capture. In gadolinium neutron capture therapy (GdNCT) a cancer patient is injected with Gd endused tracer followed by exposure to a neutron beam. Neutron absorbed by the Gd tracer produce secondary particles such as photons and electrons. While traversing tissue, the particles deposits dose and The particles travels the tissue exposed to a neutron beam, once Gd absorbs neutrons, decays and release product particles the particles is injected to the cancer patient product particles deposits dose locally to

4.1 Cross-section

Neutron capture cross section of natural Gd is given by the weighted sum of isotopic cross sections. Relative abundance of Gd isotopes in natural Gd and their neutron capture cross section are listed in table 1. Isotopes Gd-157 and Gd-155 collectively contribute 99.99% of the cross section, resulting in 48800±150 barns. Natural Gd interaction with thermal neutrons may therefore be simplified as a “two-absorbing isotope system” consisting of the isotopes Gd155 and Gd157 [Dumazert, 2018].

4.2 Reaction Equation

Since natural Gd interaction with neutrons can be ascribed to isotopes Gd-157 and Gd-155, it is worth studying their corresponding nuclear reaction equation.

$$^{155}_{64}Gd \rightarrow ^{156}_{64}Gd^{*} \rightarrow ^{156}_{64}Gd + \gamma + ICe^{-}(Q = 8.5MeV) \quad (4.1)$$

$$^{157}_{64}Gd \rightarrow ^{158}_{64}Gd^{*} \rightarrow ^{158}_{64}Gd + \gamma + ICe^{-}(Q = 7.9MeV) \quad (4.2)$$

Once a Gd nuclei has absorbed a neutron it exists in an excited energy state from which it decays by gamma-transition, resulting primarily in gamma-ray (γ-ray) emission and internal conversion (IC) electrons. Byproducts of the decay are Auger and Coster-Kronig (ACK) electrons and X-rays, prompted by vacancies left by the IC electrons, for further explanation of gamma-transition see section ??. The Q-value (Q) is defines as the difference in mass before and after a nuclear reaction and represents the net energy released when the nuclei has decayed completely. This energy is distributed as kinetic energy among product particles. Due to the Gd nuclei's large mass, compared to a photon (massless) and an electron, the recoil energy is neglectable (Modern Nuclear Chemistry, page 219*). I.e. most of the Q-value is distributed among gamma-rays and IC electrons.

4.3 Reaction Energy Spectrum

From Gd(n,gamma) capture, the excitation energy is distributed among reaction products; roughly 99% of the energy is carried by prompt gamma-rays and the rest by low energy electrons [Sakurai et al.]. The energy spectrum ranges from 0 MeV to the Q-value of the nuclear reaction. Energies of prompt gamma-rays lie all over the spectrum, while energies of IC electrons and their biproducts are mainly located at the lower end, below 0.2 MeV. The resulting spectrum is an overlap of two basic components. The first is a continuous spectrum, generated by prompt gamma-rays in the medium to high energy range, and the second is a set of discrete lines, produced by low energy prompt gamma-rays, IC electrons, Auger electrons and X-rays. In other words, prompt gamma-ray emission adds to both components, while the remaining reaction products supply just the discrete.

The spectrums form is closely related to the nuclear structure of gadolinium. Figure ? illustrates excited states of an arbitrary nucleus. A low-lying level has less excitation energy than a high lying level. Low-lying levels are easily distinguishable, each with a known spin and parity, they are discrete. As the excitation energy increases so does the nuclear level density, until high lying levels eventually become indistinguishable from one another and resemble a continuum. In fig. ?, the quasicontinuum domain of energy states is represented by a gradient, where energy level density increases as the gradient darkens. Energy levels within the quasicontinuum are marked by dotted lines and the discrete domain with uninterrupted lines. There is no clear boundary between the continuous and discrete domain, but rather a smooth transition between the two. The highest energy level represents neutron capture state and the lowest level ground state, both are indicated by a bold uninterrupted line. A transition from one level to another is indicated by and arrow.

4.3.1 Prompt Gamma-Rays

A nucleus may transition once or several times before it reaches ground state. Transitions can occur between (1) states in the continuous domain, (2) states in the discrete domain or (3)

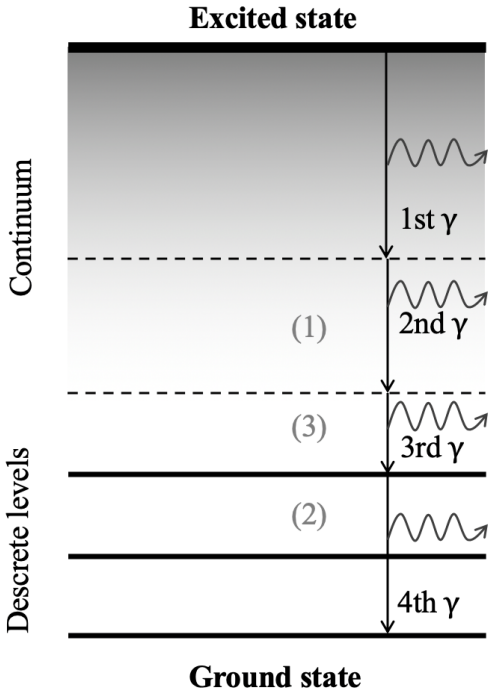

Figure 4.1: Nuclear levels of an arbitrary nucleus

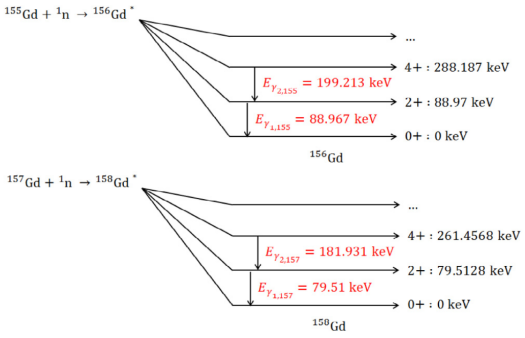

Figure 4.2: Excitation levels of Gd-155 and Gd-157* and corrosponding gamma-transitions*

between the two. In the continuous domain there are nearly endless possible states from which a nucleus can decay. It is the transitions with initial states in this domain that bring about the spectrum's apparent continuity. In the spectrum, gamma-rays take the form of a broad peak structure along with a couple of prominent spikes. The distribution stretches from one end of the spectrum to the other. The broad peak favors energies in the bottom half of the spectrum, its apex between 0 and 2 MeV, and tapers off slowly as it approaches maximum energy release.

As the nucleus de-excites and gets closer to ground state transitions between states in the discrete domain occurs. There is a limited amount of discrete levels, consequently the number of possible gamma-emission energies are finite, in contrast to the continuum. This results in discrete peaks near the lowest part of the energy spectrum.

Fig. **??** illustrates gamma-transistions associated with excited gadolinium nuclei. Two peaks, in the lower end, dominate the spectrum. In a purely isotopic material of either Gd-156* or Gd-158* a set of two energy pairs is emitted, 88.97 keV, 199.22 keV and 79.51 keV, 181.94 keV, respectively. The lowest energy of each set is characteristic for the transition between first excited state with spin-parity (J)$^{2+}$ and ground state 0^{+}, while the larger energy

is characteristic for transitions between second excited state with spin-parity 4^+ state and first excited state 2^+[C.W. Reich, Nuclear Data Sheets for A = 156, Nucl. Data Sheets 113 (11) (2012) 2537–2840.]. Gamma-ray emission rate probability (per neutron capture) of Gd-157 and Gd-155 for are listed in table ?? [Gräfe et. al]

4.3.2 Internal Conversion Electrons

Alternatively, the atom can de-excite by means of internal conversion (IC), the direct emission of an orbital electron. In gadolinium excited by neutron capture, IC is most probable for transitions from first state to ground state $(2^+ \rightarrow 0^+)$ and second state to first state $(4^+ \rightarrow 2^+)$. These transitions are responsible for 96.7% of the energy carried by IC electrons [??!]. They also happen to be the same transitions from which the discrete gamma-ray duplets, mentioned previously, are produced.

IC and gamma emission are competing decay modes. The ratio of IC decay rate λ_{ICe^-} to gamma decay rate λ_γ can be described by the internal conversion coefficient (ICC) α:

$$\alpha = \frac{\lambda_{ICe^-}}{\lambda_\gamma} \tag{4.3}$$

In cases where gamma decay is preferred the coefficient is small, perhaps even negligible, and differently when IC is preferred the coefficient is large.

The probability of IC depends on the electron shell (K,L, M, ...)and shells therefor have respective coefficients (α_K,α_L,α_M, ...).

Inner shell electrons, such as those from the K shell, are more likely to interact directly with the nucleus, since its wavefunction has finite probability of penetrating the nucleus. The probability of IC in a shell becomes less likely the further away it lies from the nucleus. In other words, internal conversion depends heavily on the atomic electron density inside the nucleus. (studie of the probability of IC from shells [ref?], table?). Consequently, odds of nuclear interaction with the K-shell is more likely than with the L-shell, than the M-shell and so on.

The total ICC is the ratio of total number of IC electrons to gamma-rays emitted by a nucleus and it can be expressed as a sum of shell coefficients:

$$\alpha_{TOT} = \sum_i \alpha_i \ , \ i = K,L,M,... \tag{4.4}$$

Transition levels of lower energy favor internal conversion. As calculated by [A.AHarms, Table 4], transitions of Gd-157* from the second lowest transition level, L-shell of the first excited state, are 3 times more likely of mediation by IC than gamma-emission. While de-excitation from higher states are less prone to IC. Already at the third excitation state, Gd-157* exhibits a low coefficient of 0.1, meaning IC electron rates are 10 times lower than gamma rates.

The energy of an IC electron is determined by the available transition energy and the binding energy of a shell.

$$E_{ICe^-} = E_T - E_{bi,i}, \ , \ i = K,L,M,... \tag{4.5}$$

IC electrons contribute to discrete lines in the 20-200 keV range. Eminent is the intensity at which specifically 71 keV electrons are produced, nearly 0.27 nc^-1 in natural gadolinium [T.Aoyama].

4.3.3 X-rays and Auger Electrons

When a conversion electron is expelled from subshell m a vacancy is left behind. Still in an excited state, the atom undergoes further de-excitation. An electron from a higher subshell p (>n) descends and fills the vacancy, releasing atomic excitation energy by either emission of x-rays or Auger electrons. X-ray emission occurs when the transition energy goes into electromagnetic radiation. Difference in binding energy makes up the x-ray energy.

$$E_{x-ray} = E_T = E_{bi,p} - E_{bi,m} \tag{4.6}$$

On the other hand, the transition energy may go into freeing an electron of an intermediate subshell n where n lies between shell m and p. The so-called Auger electron has energy equal to the difference in transition energy and binding energy.

$$E_{Ae^-} = E_T - E_{bi,n} \tag{4.7}$$

X-rays and Auger electrons, from L- and K-shell, of gadolinium-neutron capture are radiated in the 0-50 keV range. The most prominent x-ray has energy of 43 keV and an emission rate of 0.47 nc^-1 (per neutron capture). Auger electrons worth noting are of energy 35 keV (0.08 nc^-) and 5 keV (0.21 nc^-1). In comparison to x-rays, they are less frequent and of lower energies. [Dumartez]

Chapter 5

Semiconductors and Pixel Sensors

5.1 Semiconductors

5.1.1 Energy Band Diagram

?? An energy band diagram is often used to illustrate the conductive properties of an atomic structure. The vertical axis corresponds total energy of an atomic electron. The horizontal axis corresponds to the position in space in the atomic structure. Valence electrons have energies indicated by the valence band (bottom band). Free electrons that are responsible for conduction lie in the conduction band (top band). Fermi energy level represents the maximum electron energy at absolute zero temperature (0K) and lies in-between the two bands. In diagrams, the area within the bands are usually shaded to indicate allowed electron energy states. The energy bands may or may not overlap. In the latter case, there is a gap between the bands which contains forbidden electron energies. This gap it is called the band-gap. The width of the band-gap E is the difference between the lowest energy in the conduction band E_C and the highest energy in the valence band E_V. A valence electron must collect energy no lesser than E to enter the conduction band.

An insulator is a poor conductive material that does not conduct electric current. Its energy diagram shows that the gap between the energy bands are large. In fact, it is so large that electrons have great difficulty crossing the forbidden region and ever entering the conduction band. In contrast, a conductor is a highly conductive material that readily allows the flow of electric current. The valence and conduction band overlap and create a union. There is no band-gap and electrons may flow freely from one band to the other.

A semiconductor is a material whose conductivity lies between an insulators and a conductors. The conductivity depends on its temperature and composite material. Rising temperatures increase the kinetic energy of valence electrons and determine whether they have enough energy to leap over the band-gap and into the conduction band. At low temperatures a semiconductor behaves like an insulator and with increasing temperatures the conductivity rises, eventually resembling that of a conductor. The conductive properties can also be altered by doping the material with impurities. Such semiconductors are called doped or extrinsic semiconductors.

5.1.2 Doped Semiconductors

When speaking about semiconductors, doping is the process of injecting impurities into the structure. Adding impurities to a pure semiconductor alters its electrical conductivity by intro-

ducing allowed energy states in the band-gap. These impurity states appear close to either the conduction band or valence band depending on the impurity. The number of valence electrons of an impurity atom determines the doping type. Semiconductors in which added impurity atoms has an extra electron are n-type while those with impurity atoms an electron short are p-type.

The most common semiconductor material is silicon (Si). Silicon belongs in group IV of the periodic table and thus has four electrons in its outer shell. In a pure silicon crystal structure, the four outer electrons each form a covalent bond with a neighboring electron of another Si-atom. At thermal equilibrium the only accepted energy states are in the valence band. If sufficient energy, at minimum the band-gap, is transferred to valence electrons they may excite to the conduction band.

A neutrally charged phosphorous (P) atom has five valence electrons, one more than Si-atoms, and as an impurity in the Si-crystal lattice acts as an electron donor. Four out of its five electrons form covalent bonds with valence electron of neighboring Si-atoms. The fifth donor electron is left loosely bound to the P-atom and, thus, is more easily excited to the conduction band.

In contrast, a neutrally charged boron (B) atom has three valence electrons. While phosphorous supplies electrons, a boron impurity contributes to electron vacancies (or holes). The holes in the Si-structure acts as electron acceptors. Valence electrons may fill a hole and, in its wake, leave a new hole. One could also say the two charge carriers (interchange?) switch positions

Figure ?? illustrates the energy band diagram of doped semiconductors, p-type (right) and n-type (left). In p-type, donor state appears in close proximity of the conduction band and in n-type acceptor states and lie just above the valence band. The gap between an impurity state and the closest band is referred to as dopant-site energy gap and it is significantly smaller than the band-gap. Acceptor levels lift valence electrons slightly above the valence band and donator levels supply an electron in an energy state extremely close to the conduction band. Adding impurities lessens the energy required to excite an electron and consequently increases the materials conductivity.

5.1.3 The Pn-Junction

Combining extrinsic semiconductors of different type can create a diode, an electrical component which allows the easy passage of current in one direction but prohibits it in the other. The combination of a p-type and n-type semiconductor creates a pn-junction diode. The formation of a pn-junction can be seen in Fig. ?? A pn-junction is the interface between an n-type and a p-type. N-type have an excess of negative charge carriers (electrons) and p-type have an excess of positive charge carriers (holes). When two extrinsic semiconductors are joined the process of charge diffusion is set in motion. Electrons from the n-type drift towards the p-type and combine with positive charge carriers, while holes from the p-type make their way to the n-type and combine with negative charge carriers. Naturally an electric field (and a potential barrier) instantaneously forms and increases as charges accumulate in opposite regions near pn-junction. Once the potential barrier reaches an impassable magnitude the diffusion of charge comes to a halt and the system is said to have reached thermal equilibrium. The depletion region is the zone in a pn-junction where no mobile charge carriers are present and only ionized impurity atoms remain. In the depletion region, near the junction the p-type has a negative space charge region and the n-type a positive space charge region. The generated electric field only exists in the depletion region and points from n-type (positive region) to

p-type (negative region) inside the depletion region. Thus, any charge carrier that may appear in the semiconductor material moves with respect to the electric field inside the depletion region and by diffusion outside the depletion region. In other words, the pn-junction behaves like a diode, allowing current to flow freely in one direction while prohibiting it in the other.

5.1.4 The Depletion Region

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5.1.5 Reverse Bias

An external voltage source (e.g. a battery) can change the properties of a pn-junction diode. Reverse bias voltage is created by attaching (+) pole to n-side and the (-) pole to p-side such that the electric field caused by the bias points in the direction of electric field in the depletion region. Electrons on the n-side are attracted to (+) and holes to (-). The free charge carriers are pulled even further away from the pn-junction. A reverse bias this increases the depletion regions width. Oppositely, a forward bias connects (+) and (-) to poles to p-side and n-side, respectively, and pushed charge carriers closer to the pn-junction. The depletion region width decreases.

The pn-junction diode described above combined with a reverse bias acts as a very simple semiconductor particle detector. A particle traversing the depletion region ionizes composite atoms and creates electron-hole (e-h) pairs which gives rise to a pulse signal indicating the ionizing particles presence.

A pn-diode is integrated in an electric circuit with the help of electrodes; an electrical conductor used to connect non-metallic components into circuits. By the basic physical phenomenon of electrostatic induction, a moving point charge induces opposite charge in a conductor. Electron-hole pairs are created along the track of an ionizing particle traversing the pn-diode. The presence of an electric field causes electrons and holes to drift towards respective ends of the pn-diode, each welded to an electrode. The moving charge carriers induces charge in the electrodes and are responsible for the pulse signal registered by readout electronics. The induced charge grows as charge carriers accumulate and comes to a holt once complete charge collection has been achieved. The charge collection time can be shortened (i.e. improved) by increasing the electric field strength. (Figure? Pulse signal?) In a pn-diode without a bias, there is only an electric field in the depletion region. Charge carriers in the depletion region are swept away by the local electric field and induce a pulse signal. In the undepleted region there is no electric field and charge carries in this region are subject to charge recombination with majority carriers. Hence the induced signal owes its realization to charge generated in the depletion. With reverse bias the depletion region becomes larger and its local electric field increases. A larger depletion region means more signal inducing charge carriers can be produced. Since charge carriers in the depletion region experience a stronger electric field they accelerate and are, thus, collected faster.

As a particle detector the pn-diodes depletion region is considered the sensitive volume. It is the charge carriers produced in this area who are responsible for pulse generation observed by the readout electronics. The amount of charge and collection time thereof plays a role in the detector's sensitivity. A pn-diode coupled with reverse bias enlarges the sensitive volume, giving room for greater charge production and faster signal generation. Reverse bias thus improves the spatial, energy and time resolution of the detector.

5.2 Pixel Sensors and MAPS

5.2.1 CMOS Technology

Complementary metal–oxide–semiconductor (CMOS) is a fabrication method used to integrate transistors on a piece of semiconductor, usually silicon. MOS is a type of transistor fabricated by the oxidation of a semiconductor. In pMOS transistors, source (S) and drain (D) are connected to p-wells in an n-type substrate. Inversely, in nMOS transistors, source and drain are connected to n-wells in a p-type substrate. The gate-source voltage V_GS controls the conductivity over the transistor. The potential difference gives rise to an electric field between gate and substrate. In nMOS, a positive voltage (with respect to ??) attracts substrate electrons to gate and pushes holes away. With sufficient magnitude gate-source voltage can cause partial inversion, turning a fraction of the p-doped substrate into n-type. This creates an n-channel (hence nMOS) connecting source and drain and allows electron flow between the two. Increasing V_GS thickens the channel and opens up for greater electron current, increasing conductivity. Similarly, negative gate-source voltage can be applied to pMOS to create a p-channel. Charge carriers of nMOS and pMOS are electrons and holes, respectively.

A voltage can also be applied such that an electric field occurs between source and drain. In nMOS, (a pos/neg voltage with respect to ??) causes the n-channel to retract away from the drain. The channel becomes asymmetrical, its thickness tapers off as it approaches D (fig. ??). Increasing drain-source voltage (V_DS) can completely disconnect the channel from drain. Though S and D are no longer directly connected, current can still flow. Between the "pinched off" channel tip and drain there is a depleted area where charge can drift. While a uniform n-channel permits current in both directions, the disconnected asymmetrical channel is unidirectional. This mode of operation is called saturation mode. In saturation mode, further increase of V_DS does not cause current to increase. Electrons are sped up by V_DS to a point where they reach carrier velocity saturation (i.e. maximum velocity) and the current is said to be saturated and constant. [R. Jacob Baker] At this point, raising gate-source voltage can be used to amplify the current.

In a circuit, a saturated MOS transistor works like a switch, current either flows (switch ON) or doesn't (switch OFF). If input voltage applied to G is high, an n-channel forms in nMOS and current passes though, the switch is "ON". In pMOS, a high input voltage does not create a p-channel and no current passes the transistor, the switch is "OFF". Reversely, a low voltage turns nMOS "OFF" while pMOS "ON".

By controlling the conductivity, electronical signals can be amplified or switch on/off. ("wiki") The combination of the complementary pMOS and nMOS semiconductors in a circuit, create a CMOS transistor (pMOS + nMOS = CMOS) as shown in Fig. ??.

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5.2.2 Active Pixel Sensors

A pixel sensor is an imaging sensor earlier restricted to light applications. In later years pixel sensors have been developed to also detect energetic particles. The smallest sensing unit of a pixel sensor is a pixel. A matrix of pixels forms a larger sensing area and together with the proper stimulus (light or ionizing particles) they can generate an image. The image granularity (spatial resolution) is determined by the pixel size; a large pixel gives low granularity, few pixels fit in a matrix, and a small pixel gives high granularity, many pixels fit in a matrix.

The sensitive mechanism in a pixel is a configuration of semiconductors (photodiodes)

which generate a pulse signal as a consequence of ionizing radiation traversing its sensing volume There are two types of pixel sensors, active and passive. The main difference between an Active Pixel Sensor (APS) and a Passive Pixel Sensor (PPS) is that the former incorporates one or more amplifying transistor (MOSFET transistors) while latter does not. Pixels in PPS are read out without amplification. Transistors in an APS convert generated charge to a voltage, amplify the voltage signal and remove noise. These characteristics make APS superior to PPS which has high noise and slow readout rates in comparison.

5.2.3 MAPS

In the early 1990s, APS based on CMOS technology was proposed and at the end of the decade their application in particle physics. CMOS APS implement a monolithic pixel architecture (Fig.??b), with transistors built into the pixel itself. In contrast, a hybrid architecture (Fig.?? a) constitutes of individually manufactured pixel and readout electronics coupled by the means of bump bonding. A Monolithic APS (MAPS)...

Chapter 6

The ALPIDE Sensor

Alice Pixel Detector (ALPIDE) is a monolithic active pixel sensor (MAPS) based on TowerJazz 180 nm CMOS technology. The sensor was created for the upgrade of the Inner Tracking System (ITS) of the ALICE experiment at CERN. Since 2012, several prototypes of the ALPIDE has been developed. [] The final, optimized chip was validated in 2016 after substantial test-beam campaigns that show performance values beyond the requirements set by the ITS upgrade, listed in table ??. [G.Rinella 2016] The chip has a high detection efficiency (>99%), short deadtime (<$10^{-}5$ pixel^{-} event^{-}) and excellent spatial resolution (5um) for tracking charged particles.

6.1 Chip Layout

ALPIDE measures 15 cm by 30 cm and contains more than five hundred thousand pixels, organized into 512 rows and 1024 columns??. [Abelev 2014 ?]. Each pixel has a surface area 29.24 m × 26.88 m and a sensing diode (diameter 2 um) who is approximately 100 times smaller than the pixel area. The peripheral region (1.2 x 30 mm^2) implements analog biasing, control, readout and interfacing functionalities. [G. Rinella 2016] The chip is mostly made out of silicon (40 um thick) and is topped off with 11um of aluminum.[?] A 3D cut-out of the chip is presented in figure ??.

The pixel matrix is grouped into 32 sections with 16 columns in each (16 col/sect x 32 sect = 512 col). During readout, sections are read out simultaneously and columns sequentially. Readout is controlled at the chip periphery. For every double-column, there is a dedicated priority encoder. Priority encoders are responsible for generating hit pixel addresses and sending said addresses to the periphery.(?) An illustration of the chip as a whole is presented in fig?? [pCT He Ions]

6.2 Pixel Features

A cross-sectional view of a pixel is illustrated in fig ??. The sensor is realized on a silicon substrate on which a highly resistive epitaxial layer (the active volume) is grown. The possible thicknesses of the active layer ranges from 18um to 30um.

P-wells are placed into the epitaxial layer. A potential barrier forms where the heavily p-doped (P++) substrate and (P+) wells meet the lightly p-doped (P-) epitaxial layer. Electrons (e) are vertically confined by the potential barriers and diffuse laterally across pixels.

The ALPIDE chip is based on the 180 nm CMOS technology of TowerJazz. An important design feature is the deep p-well which shields n-wells of the pMOS transistor from the active layer. This prohibits diodes and n-wells from competing in collecting electrons. The feature allows the full use of CMOS circuitry in the epitaxial layer without impairing charge collection [S. Kushpil (2017)].

The n-well diode, i.e. sensing element of the pixel, is surrounded by a depletion volume. Moderate reverse bias can be applied to the substrate to increase the depletion volume and improve charge collection. [S. Kushpil (2017)] The epitaxial layer is, for the most part, free of electric fields and the charge is left to thermally diffuse in the active volume until it is collected by the diode or recombines with the atomic structure. Because of this, MAPS, in general, have slow collection times of approximately 100ns. [*]

6.3 In-Pixel Front-End Circuit

Each pixel (28x28 um^2) embodies a collection diode and a front-end circuit. [G. Aglieri]. The in-pixel circuit, as shown in fig??, comprises an input stage, an analog front-end and a digital front-end. Analog front-end When hit by ionizing radiation, the active volume generates electron-hole pairs. The generated electron charge accumulates around the collection diode and induces a voltage signal in the input stage (fig.?? (a)). The continuous signal travels to the analog front-end where it is shaped and amplified by an amplifier. The amplifier works as a delay line, with a peaking time of 2us, and enables ALPIDE to be run in trigger mode. Also part of the analog front-end circuit is a comparator. The comparator has two analog inputs OUT_A and THR and a digital binary output OUT_D (0 or 1?). If the amplified signal OUT_A exceeds a fixed threshold voltage THR the comparator outputs a pulse OUT_D. The period of the output is typically 5-10 us.

The pulse continues to the digital front-end where it encounters a STROBE signal. The STROBE signal provides a framing interval (a window) of a few nanometers. It is distributed globally to all pixels and can be activated either internally or externally. If the pulse from the analog front-end coincides with a window hit information is latched on to one of the three in-pixel memory cells. These memory cells are in-pixels data storage elements also known by the collective term multi-event buffer (MEB). MEB can store up to three hits simultaneously, one per buffer (i.e. memory cell).

6.4 Mode of Operation

Chip operation mode is determined by STROBE trigger settings. Continuous mode implements internal triggers while trigger mode relies on external provocation to generate a STROBE signal.

Chapter 7

Geant4 Simulations

7.1 MC method and Geant4

7.2 Detector Geometry

7.3 Set-up

7.4 Results

Chapter 8

Testing

8.1 Cyclotron Radiation Environment

Cyclotrons are particle accelerators used to speed up light particles (e.g. protons). Figure ?? presents a simplistic representation of a cyclotron under operation. Accelerated particles are directed towards a target, which is placed inside a "target box" located at the end of the collision chamber. When the particles and the target nuclei collide, nuclear reactions take place.

In a PET center, cyclotrons are used to activate radioactive tracers such as F-18. The radioisotope is the end product of proton-O-18 fusion. The nuclear reaction produces F-19, an unstable isotope which decays by neutron emission to become F-18*.

$$O-18(p,n)F-18 : O-18+p \rightarrow F-19* \rightarrow F-18*+n \tag{8.1}$$

Operations of PET cyclotrons generates large amount of radiation. In addition to F-18 neutrons, bremsstrahlung, gamma rays and neutrons of different origin are also present. Bremsstrahlung occurs during acceleration of charged particles. After neutron emission, 18-Fluoride de-excites by means of gamma-ray emission – the sole purpose of its application in PET. In other words, gamma-rays infiltrates the space which surrounds the cyclotron. Interactions between bremsstrahlung radiation and the cyclotron body, as well as secondary reactions are also sources neutron production [Y. Ogata (2011)]. Inside the target box, for instance, measurements made by [Y. Ogata (2011)] suggests the presence of fast neutrons (>8.7 MeV). Thermalization of neutrons due to scattering off the walls and cyclotron? In other words, the neutron environment surrounding cyclotrons is messy.

The detector in question implements gadolinium (a high Z material) for neutron conversion and silicon for particle detection. Gadolinium is a high Z material and consequently prone to photoelectric gamma-ray interference (i.e. ionization). It is also highly reactive to thermal neutrons but less so for slow and fast neutrons. The foil is activated upon thermal neutron impact and radiates IC electrons and gamma radiation. Conversion electrons generate a strong signal in the detector. High energy gamma-rays are inherently oblivious to the detector and do not interfere with the electron signal. Following internal conversion is emission of characteristic x-rays, prominently from K_{alpha} transitions. Furthermore, gadolinium activation can also be caused by gamma-induced excitation [Kand rays, gadolinium is ionized and attains an excited state from which it relaxes by means of x-ray emission. Thus, x-rays originate not only from neutron capture, but also from background gamma-rays.

The thin semiconductor detector is supposedly more sensitive to x-rays than energetic

gamma-rays [Kandlakunt 2012]. In a neutron field the infiltration of gamma-rays can become problematic. With sufficiently high gamma-ray intensity the production of x-rays from gamma induced excitation combined with x-rays from neutron capture may overshadow electron signals.

8.2 Set-up

8.3 Results