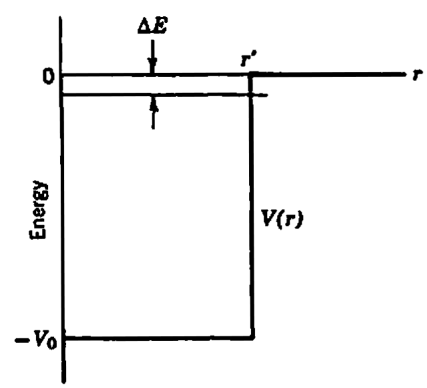
Chapter 17: Introduction to Elementary Particles

The **strong force** is responsible for the stability of nuclei. Since it can be studied by measuring the forces between nucleons, it is also frequently called the **nucleon force**. The strong force has the following features:

- The strong force is the strongest force we know off. The strong force is 100 times stronger than the Coulomb force; it is 10^{40} times stronger than the gravitational force.
- The strong force is attractive. The strong force keeps nucleon together and overcomes the repulsive forces between the protons in a nucleus.
- The strong force has a short range. It is not important beyond distances of 2 fm. It does not influence the interaction between nucleons at large distances.
- The strong force is independent of electric charges. The strong force between protons – protons, protons – neutrons, and neutrons – neutrons is the same. Light nuclei have equal numbers of protons and neutrons: $N = Z$.
- The strong force saturates. The measured binding energy per nucleon is independent of the number of nucleons, indicating that nucleons only interact with a limited number of other nucleons. This is consistent with the short-range nature of the strong force.

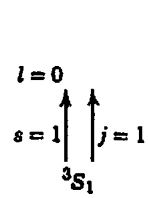
The lightest nucleus in which the strong force plays a role is the deuteron. The deuteron has the following properties:

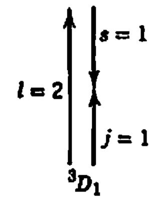
- The deuteron has one proton and one neutron. Since the neutron has no charge, the Coulomb force does not play a role.
- The deuteron is weakly bound. The ground state is located at -2.2 MeV, and no bound excited states are known. This information can be used to estimate the shape of the potential well associated with the strong force. If we assume that the potential associated with the strong force is a square-well potential with a radius consistent with the size of the deuteron, we can adjust the depth of the well until we have only one eigenstate with an energy of -2.2 MeV. The required depth of the potential is -40 MeV. Note: this depth is small compared to the rest energy of the proton which is 930 MeV.



- The deuteron has even parity. This implies that the orbital angular momentum of the wavefunction of the deuteron must be even.

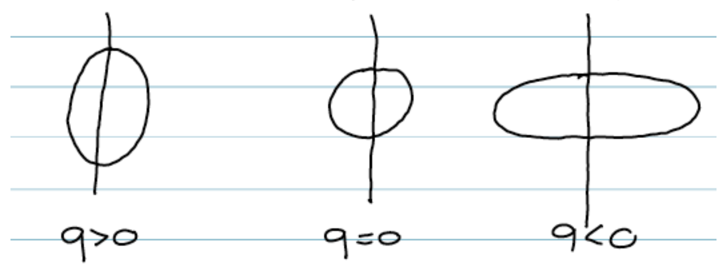
- The deuteron has a nuclear spin equal to 1. This implies that the total angular momentum of the deuteron must be 1 (j = 1). The spin of each nucleon is ½ and the total spin of the two nucleons can thus be 0 or 1. If s = 0, the orbital angular momentum must be 1 but this is not allowed due to the parity of the deuteron. We thus conclude that the total spin must be 1 (spin triplet). This implies that the orbital angular momentum must be 0 or 2. The two possible states of the deuteron are thus the $^3S_1$ state and the $^3D_1$ state. The ground state of the deuteron is dominated by the $^3S_1$. However, it can not be a pure states since any eigenfunction with an orbital angular momentum equal to 0 has spherical symmetry: the observed asymmetry of the charge distribution can be introduced by adding a small $^3D_1$ component to the ground-state wavefunction.





  The deuteron is not observed to have a $^1S_0$ state. This indicates that the nucleon potential must have a spin dependence. The potential must be weaker if the spins of the nucleon pair are anti parallel (s = 0) instead of parallel (s = 1). This explains why we do not see bound states of two protons and bound states of two neutrons. Since the Pauli exclusion principle applies when we consider a proton pair and a neutron pair, the nucleons must be in a state in which the spins are anti-parallel (s = 0) but this state is not bound.

- The deuteron has a small **electric quadrupole moment** q = 2.7 × 10^{-31} m^2. This requires a non-spherical charge distribution. In the diagram on the right, the relation between the sign of the electric quadrupole moment and the shape of the charge distribution is illustrated. The electric quadrupole moment is defined as

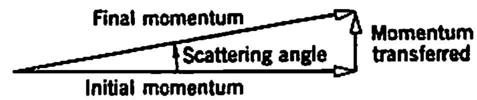


$$q = \int \rho(x,y,z)\left(3z^2 - \left(x^2 + y^2 + z^2\right)\right)d\tau$$

  The measured quadrupole moment of the deuteron is can be explained if we assume that the ground state of the deuteron is a mixture of 96% of the $^3S_1$ state and 4% of the $^3D_1$ state. The fact that the ground state of the deuteron is not a pure $^3S_1$ state requires that the nucleon potential does not have spherical symmetry.

- The deuteron has magnetic dipole moment of +0.857 μ_n. The magnetic dipole moment is thus not equal to the sum of the dipole moments of the proton and the neutron.

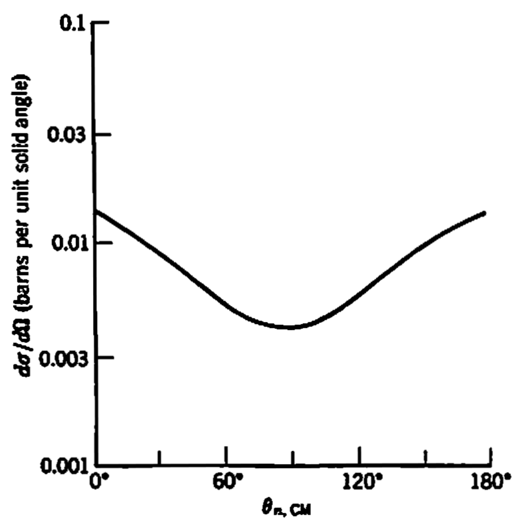
- The deuteron has a charge distribution with a radius of 2.1 fm.



The details of the nucleon force have been explored with nucleon scattering experiments. In scattering experiments, the change in the linear momentum of the projectile is measured and used to determine the effect of the force involved in the scattering process. The following relation is expected between the change in the linear momentum of the projectile and the properties of the force:

$$\frac{\Delta p}{p} = \frac{F\Delta t}{p} = \frac{F\left(\frac{\Delta r}{v}\right)}{mv} = \frac{F\Delta r}{mv^2} = \frac{F\Delta r}{2K} = \frac{V_0}{2K}$$

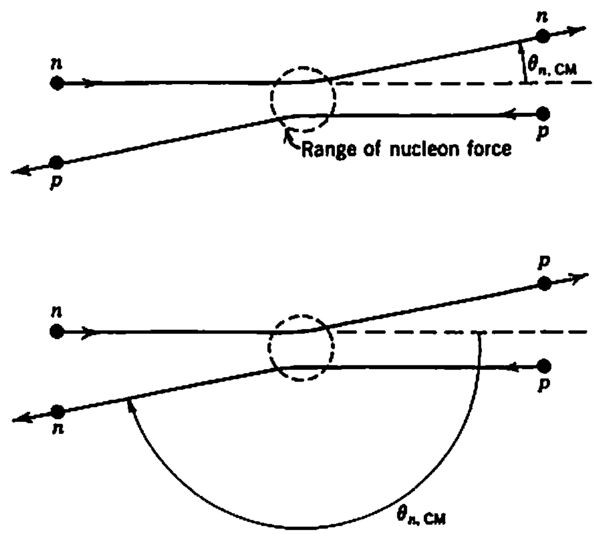
where Δr is the range over which the force F acts. The last step in this equation uses the relation between potential and force: $F = -dU/dx$.



In a typical scattering experiment the kinetic energy of the projectile may be 90 MeV. If the interaction potential has a depth of 40 MeV (which is consistent with the binding energy of the deuteron), the fractional change in the linear momentum of the projectile is expected to be about 25%.

The yield of neutrons scattered from protons as function of scattering angle is shown in the Figure on the right. A small deflection angle requires a small impulse and, assuming a constant force, a small distance over which the force is acting. A small deflection angle is thus correlated to a small momentum transfer. The surprising observation made in the scattering experiments was the increase in yield at large angles and the symmetry of the scattering distribution around 90°. Large scattering angles require a large impulse and are correlated with large momenta transfer; it was not expected that this process occurs with the same probability as scattering at forward angles.

This surprising result was explained in terms of an exchange force, which changes a proton into a neutron and vice versa. This process is schematically indicated in the Figure on the next page. The presence of this process requires an operator, called the **exchange operator** that is usually written as P. The scattering potential describing this process can be written as



$$V_{scatter} \simeq \frac{1}{2}\left(V(r) + V(r)P\right)$$

The scattering cross section is proportional to $\psi_f^* V_{scatter} \psi_i$. The product of the scattering potential and the initial wavefunction can be written as

$$\begin{aligned} V_{scatter}\psi_i &= \frac{1}{2}\left(V(r) + V(r)P\right)\psi_i = \\ &= \frac{1}{2}V(r)\psi_i + \frac{1}{2}V(r)P\psi_i \end{aligned}$$

The exchange operator changes the proton into a neutron and vice versa. As a consequence, the effect of the exchange operator for a two-nucleon system with one proton and one neutron

$$P\psi_i = (-1)^\ell \psi_i \quad \Rightarrow \quad V_{scatter} = \frac{1}{2}\left(V(r) + V(r)P\right) = \frac{1}{2}V(r)\left(1 + (-1)^\ell\right)$$

This potential is also called the **Serber potential**. We note that when the orbital angular momentum is odd, the scattering potential is 0; when the orbital angular momentum is even, the scattering potential is V. The nucleon potential thus depends on the orbital angular momentum of the interacting nucleons.

We can use a classical picture to connect a certain kinetic energy K to a certain orbital angular momentum. Consider a state with an orbital angular momentum ℓ. If we look at this system in the center-of-mass reference frame of the two nucleons, we must require that each nucleon has a linear momentum p obtained in the following manner:

$$L = \sqrt{\ell(\ell+1)}\hbar \approx p\left(\frac{r}{2}\right) + p\left(\frac{r}{2}\right) = pr \quad \Rightarrow \quad p = \frac{\sqrt{\ell(\ell+1)}\hbar}{r}$$

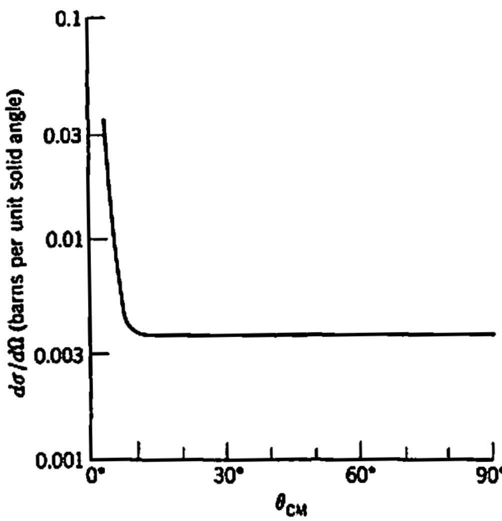
where r is the largest distance at which the strong force acts. The kinetic energy of the two nucleons is thus be equal to

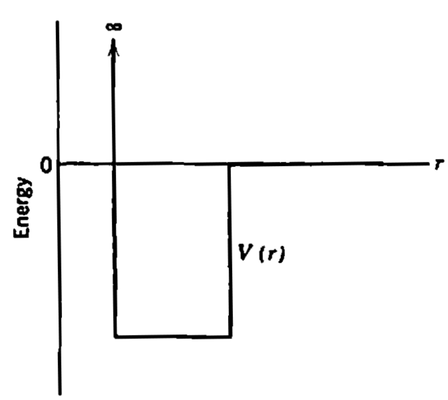
$$K_p + K_n = 2\frac{p_n^2}{2m_n} = \frac{\ell(\ell+1)\hbar^2}{m_n r^2}$$

If the orbital angular momentum parameter is equal to 1, the total kinetic energy is 20 MeV. If $\ell = 2$, the total kinetic energy is 60 MeV, etc. If the kinetic energy is less than 20 MeV, the distance *r* must increase in order to achieve $\ell = 1$ but an increase in *r* creates a separation between the nucleons that is larger than the range of the strong force and as a result, the $\ell = 1$ scattering process is not influenced by the strong force. Consider the following examples:

- ***K* = 40 MeV**. The scattering process will only be influenced by $\ell = 0$ and $\ell = 1$ scattering. But, for $\ell = 1$ $V(r)$ = 0 and the scattering process only involves $\ell = 0$ contributions. The wavefunctions associated with $\ell = 0$ have spherical symmetry and the scattering process is thus isotropic.

- ***K* = 330 MeV**. At this energy, the maximum orbital angular momentum parameter that can contribute is $\ell = 3$. Since for odd values of ℓ the scattering potential is 0, we only need to consider even values of ℓ. The scattering process is thus determined by the scattering associated with $\ell = 0$ and $\ell = 2$. Since the scattering for $\ell = 2$ is not isotropic, we do not expect an isotropic scattering distribution. However, the observed angular distribution, as shown in the Figure on the right, is isotropic at angles larger than 10°. This can only be explained by destructive interference between $\ell = 0$ and $\ell = 2$. Destructive interference requires a repulsive core in the nucleon potential. The modified nucleon potential can be represented by the diagram shown in the Figure on the right. The repulsive core impacts the $\ell = 0$ wavefunction and has little impact on the $\ell = 2$ wavefunction. The repulsive core is also responsible for the saturation of the nuclear force. Without the repulsive core, all nucleons would be in a sphere of about 2 fm and the binding energy would be proportional to *A*. With the repulsive core, the nucleons in the nucleus are separated by on average 1.2 fm and each nucleon only interacts with its closest neighbors.

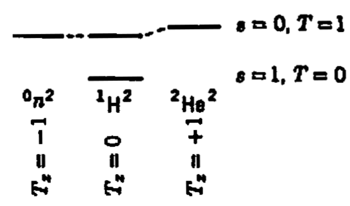




Other information obtained for the nucleon force between a nucleon pair shows that it depends on the total spin of the two nucleons, on their orbital angular momentum, and on the total angular momentum of the nucleons. The dependence on the total angular momentum implies that the nucleon force contains a spin-orbit term. The net spin-orbit interaction for the inner nucleons in a nucleus is 0; the spin-orbit interaction is non-zero for edge nucleons.

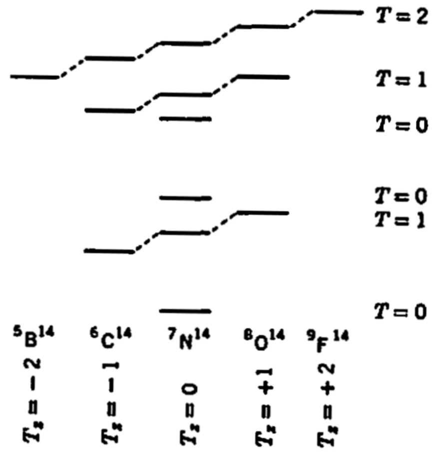
Based on the information discussed so far, we come to the following conclusions about the nucleon potential:

- The nucleon potential is charge independent.
- The Pauli exclusion principle prohibits certain interactions. For example, the wavefunction describing the $^3S_1$ state of a two nucleon system has $\ell = 0$, $j = 1$, and $s = 1$ and is symmetric. The np system does not need to satisfy the Pauli exclusion principle and the wavefunction describing this system can thus be symmetric. However, the wavefunction for the 2n and 2p systems must be asymmetric and these systems can thus not be described by a $^3S_1$ wavefunction. Other states that cannot occur for a 2n or a 2p system are for example:
    - $^1P_1$: $\ell = 1$, $j = 1$, $s = 0$ and has a symmetric wavefunction.
    - $^3D_{1,2,3}$: $\ell = 2$, $j = (1,2,3)$, $s = 1$ and has a symmetric wavefunction.
- The nucleon potential will be close to 0 when ℓ is odd. For even ℓ the nucleon potential will be non-zero.
- For a nucleon-nucleon pair in a singlet state, there is no bound state. For the triplet state there is one bound state. This state can only be occupied by a neutron and a proton (and not 2 protons or 2 neutrons).



Since the nucleon force is independent of the charge, we do not expect to see any difference between nn, np, and pp interactions except as a result of constraints imposed by the Pauli exclusion principle. In order to reflect the charge independence, we introduce the concept of **isospin** $\boldsymbol{T}$. Isospin has properties that are similar to the properties of spin. In nuclei, isospin can be used to group related energy levels in systems with the same number of nucleons (**isobars**). Examples of the grouping of states are shown in the energy level diagram for the two-nucleon system. The ground state of the deuteron has an isospin $T = 0$; the $s = 0$ states in the two-nucleon system have $T = 1$. There are $(2T + 1)$ states with the same isospin, and there are thus 3 $T = 1$ states.

In the 14 nucleon system we can observe states with $T = 0$, $T = 1$, and $T = 2$, as can be seen in the Figure on the right. Neutrons and protons are considered to be identical particles with an isospin of ½: protons and neutrons differ by their T_z values:



$$T_z = \frac{Z-N}{2}: \begin{cases} T_z = \dfrac{1}{2} & \text{for protons} \\ T_z = -\dfrac{1}{2} & \text{for neutrons} \end{cases}$$

Since a proton and a neutron differ on the basis of their T_z value, they are distinguishable. The total wavefunction of a two-nucleon system is thus the product of a spatial wavefunction, a spin wavefunction, and an isospin wavefunction:

$$\psi = \psi_\ell \psi_s \psi_T$$

Since nucleons are spin ½ particles, the total wavefunction must be asymmetric. The four energy levels of the two-nucleon system shown in the Figure on the previous page all have $\ell = 0$. The spatial wavefunction is thus symmetric. Since the two nucleons are fermion, the total wavefunction has to be asymmetric, and the product of the spin and the isospin wavefunction must thus be asymmetric. Since the singlet spin state is asymmetric, the isospin wavefunction must be symmetric and singlet spin wavefunctions must be associated with asymmetric isospin wavefunctions ($s = 0$, $T = 1$). For the same reason, triplet spin wavefunctions must be associated with single isospin wavefunctions ($s = 1$, $T = 0$)

Although, as a result of the nuclear force, the energy of states with the same isospin should be the same, their energies may differ due to the Coulomb potential, which is charge dependent. For example, for the two-nucleon system the $T = 1$ states for ${}^0n^2$ and ${}^1H^2$ have the same energy since one or both nucleons are neutral and the Coulomb potential of the system is thus equal to 0. The $T = 1$ state in ${}^2He^2$ is located at a slightly higher energy than the $T = 1$ states for ${}^0n^2$ and ${}^1H^2$ due to the Coulomb repulsion between the two protons. This confirms that the nucleon force does not depend on T_z. In the 14-nucleon system we also see that the energy of the $T = 2$ states increase with increasing Z since increasing Z is associated with an increase in the Coulomb repulsion between the protons.

Experimental evidence shows that **isospin is conserved**. For example, consider the following reaction:

$$^{1}H^{2} + {}^{8}O^{16} \rightarrow {}^{7}N^{14} + {}^{2}He^{4}$$

The ground states of H and O have $T = 0$. Since He has a high-lying first excited state, if this reaction occurs at low initial energies, He will be in the ground state, which has $T = 0$. The ground state of N has $T = 0$; the first excited state of N has $T = 1$. Experiments show that the N produced in this reaction is in the ground state; the first excited state of N is not populated in this reaction.

Conservation of electric charge implies also that $\boldsymbol{T_z}$ **is conserved**.

Models developed to describe the nucleon or strong force interpreted the force as being the result of the exchange of a force carrier. The **meson theory** was developed by **Yukawa** to describe the strong force in terms of pion exchange. The model featured the following key elements:

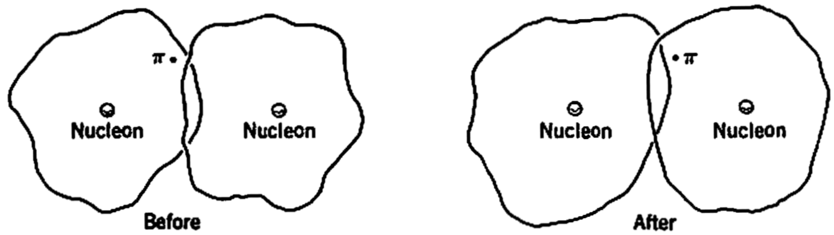
- A nucleon creates a **virtual pion**.
- The pion is assumed to have a mass, and as a result, the creation of the pion is accompanied by the change in the energy of the system. This change in energy is equal to

$$\Delta E = m_\pi c^2$$

- The Heisenberg uncertainty principle will allow this change of energy, as long as the time period during which the virtual pion exists is short enough such that

$$\Delta E \Delta t = \frac{\hbar}{2} \quad \Rightarrow \quad \Delta t = \frac{\hbar}{2\Delta E} = \frac{\hbar}{2m_\pi c^2}$$

- The pion is assumed to travel with the speed of light and returns to the nucleon within a time period Δt.
- When two nucleons are close, it is possible that the virtual pion is not absorbed by the nucleon that emitted it, but by the other nucleon. When this happens, we say that the nucleons feel the strong force. This requires that the nucleons are close enough so that their virtual pion clouds overlap. This is schematically shown in the diagram on the next page.



- The maximum distance that the pion travels away from the nucleon is equal to

$$\text{Range} = \frac{1}{2}(c\Delta t) = \frac{\hbar}{4m_\pi c}$$

- The range of the nucleon force is about 2 fm, and the corresponding mass of the pion must be

$$m_\pi c^2 = \frac{\hbar c}{4\text{Range}} = \frac{\left(0.6582\times10^{-15}\right)\left(2.998\times10^{8}\right)}{4\left(2\times10^{-15}\right)} = 25\text{ MeV}$$

  Note: different approximations may or may not include the factor of 4 in this equation, and estimates of the mass of the pion thus range from 25 MeV to 100 MeV.

- When the mass of the force carrier decreases, the range of the force increases. The electromagnetic force is due to the exchange of photons. Since a photon has no mass, the range of the electromagnetic force is infinite.

The particle predicted by Yukawa was found in 1947. The pion comes in three forms: two pions are charged (+*e* and -*e*) and one pion is neutral. The rest energies of these pions are:

$$m_{\pi^+}c^2 = m_{\pi^-}c^2 = 140\text{ MeV}$$
$$m_{\pi^0}c^2 = 135\text{ MeV}$$

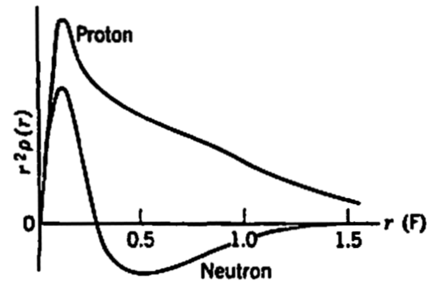
Since the pions can be charged, they can be involved in the change of a proton into a neutron and vice versa. For example:

$$n \to p + \pi^- \quad p + \pi^- \to n$$
$$p \to n + \pi^+ \quad n + \pi^+ \to p$$

When neutral pions are exchanged, no exchange of identity occurs:

$$n \rightarrow n + \pi^0 \quad p \rightarrow p + \pi^0$$

The meson theory helps us explain the magnetic dipole moment of the neutron. Although the net charge of the neutron is 0, the charge density of the neutron is non-zero, as shown in the Figure on the right, and thus produces a non-zero magnetic dipole moment.



The following other properties of pions are relevant for our understanding for nucleon interactions:

- **Pions are bosons and the spin of the pion is 0**. This conclusion is based on studies of pion creation in the following type of reactions:

$$\underbrace{p + p}_{\text{2 fermions}} \rightarrow \pi^+ + \underbrace{d}_{\text{2 fermions}}$$

  Since for an isolated system the number of fermions is constant, we must conclude that a pion is not a fermion. It thus must be a boson. This was indeed confirmed in experiments aimed at measuring the spin of the pion.

- **Pions have odd parity**. This conclusion is obtained from the study of pion capture on deuterons. Consider the following capture reaction:

$$\underbrace{\underbrace{\pi^-}_{\text{spin 0}} + \underbrace{d}_{\text{spin 1}}}_{\substack{\text{Captured in an } \ell = 0 \\ \text{state. The total angular} \\ \text{momentum is thus } j = 1.}} \rightarrow \underbrace{n + n}_{\substack{\text{If } s = 0,\ \ell = 1. \\ \text{If } s = 1,\ \ell = 0, 1, 2.}}$$

  The wavefunction of the two neutrons must be asymmetric. If the two neutrons are in the spin triplet state, the orbital angular momentum cannot be 0 or 2 since the total wavefunction would be symmetric. The orbital angular momentum of the two neutrons must thus be 1. The parity of the final state is determined by orbital angular momentum and is equal to $(-1)^1 = -1$; the parity of the neutron does not matter since the product of their parities is always +1. The parity of the initial state must also be -1. The following information is available on the parity of the initial state:

  - The ground state of the deuteron is a mixture of $\ell = 0$ and $\ell = 2$ wavefunctions. The parity of the ground state is thus $(-1)^{\text{even}} = +1$.

- The orbital angular momentum of the pion is $\ell = 0$. The parity associated with the orbital motion of the pion is thus $(-1)^0 = +1$.
- The parity of the pion is unknown.
- The parity of the initial state is thus equal to the parity of the pion.

Since the parity of the initial state must be odd, we conclude that the parity of the pion must be odd.

This method can be used to determine the parity of bosons, but is cannot be used to determine the parity of fermions. As a result, we have to use a convention to define the parity of nucleons. Our convention will be to **assign a positive parity to nucleons**.

- The three pions can be considered to be three manifestations of the same $T = 1$ particle:

$$\begin{aligned} T_z &= -1: \quad \pi^- \\ T_z &= 0: \quad \pi^0 \\ T_z &= 1: \quad \pi^+ \end{aligned}$$

- The electric charge is related to T_z:

$$\text{Nucleons:} \quad Q = T_z + \frac{1}{2}$$
$$\text{Pions:} \quad Q = T_z$$

The general rule obtained from these observations is that

$$Q = T_z + \frac{B}{2}$$

where B is the baryon number. The baryon number of a nucleon is 1; the baryon number of a pion is 0. Note that **baryon number is conserved**.

- When we compare the properties of particles and anti particles we see that:
  - The baryon number changes signs. The baryon number of a proton is +1; the baryon number of an anti-proton is -1.
  - T_z for an anti-particle is the opposite of T_z of the corresponding particle.

Applying this to the pions we conclude that:
  - The anti-particle of the π^+ is the π^-.
  - The anti-particle of the π^- is the π^+.
  - The π^0 is its own anti-particle.

- Charged pions have a long lifetime. This implies that the decay involves a force that is weaker than the nuclear and the electromagnetic force.
  Note: the following lifetimes are associated with the following three forces:
  - 10^{-23} s: this time is characteristic for the strong force. The range of the strong force is 2 fm. Assuming that the force carrier moves with the speed of light we can the time required to cover this distance is $2 \times 10^{-15} / 3 \times 10^{8} = 0.7 \times 10^{-23}$ s.
  - 10^{-16} s: typical timescale associated with the electromagnetic force.
  - $> 10^{-8}$ s: typical timescale associated with the weak force. The lifetime of the pion is 2.6×10^{-8} s.

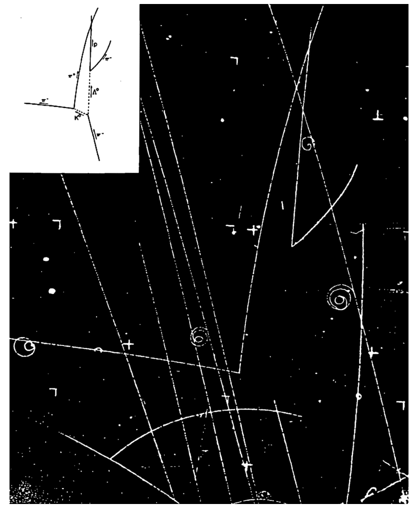
The use of particle accelerators has allowed us to create many unstable particles. The particles we have studies can be grouped into three **particle families**:

- **Baryons**: the best-known examples of baryons are the proton and the neutron. Baryons have a quark structure (three quarks).
- **Mesons**: the best-known example of a meson is the pion. Mesons also have a quark structure (two quarks).
- **Leptons**: the best-known example of a lepton is the electron (rest energy is 0.511 MeV). The next heaviest lepton is the muon (rest energy is 106 MeV). The heaviest lepton is the tau (rest energy is 1784 MeV). Each of these particles has a neutrino associated with it and its anti particles. Lepton number is a conserved quantity:

$$\sum L_e = \text{constant}$$
$$\sum L_\mu = \text{constant}$$
$$\sum L_\tau = \text{constant}$$

For the electron-like particles, the lepton numbers are defined as follows:

$$e^- : \quad L_e = +1, L_\mu = 0, L_\tau = 0$$
$$e^+ : \quad L_e = -1, L_\mu = 0, L_\tau = 0$$
$$\nu_e : \quad L_e = +1, L_\mu = 0, L_\tau = 0$$
$$\bar{\nu}_e : \quad L_e = -1, L_\mu = 0, L_\tau = 0$$



The study of interactions between particles shows that other quantum numbers must be introduced in order to account for the observations. One of these quantum number is **strangeness**. Consider the following reaction that is observed in cosmic-ray events and shown in the Figure on the right:

$$\pi^- + p \underbrace{\rightarrow}_{\substack{\text{Strong interaction.}\\ \text{Large probability.}}} V^0 \underbrace{\rightarrow}_{\substack{\text{Weak interaction.}\\ \text{Long lifetime.}}} \pi^- + p$$

The observations are weird. Time reversal symmetry would suggest that both reaction rates should be the same. The problem was solved by assuming that two particles are produced in the first step while one of them decays to produce the decay products seen in the second step.

$$\pi^- + p \underbrace{\rightarrow}_{\text{Strong Interaction}} \Lambda^0 + K^0$$

$$\Lambda^0 \underbrace{\rightarrow}_{\text{Weak Interaction}} \pi^- + p$$

The intermediate particles carry a property called **strangeness**. We make the following assignment:

Λ^0 has strangess S = -1

K^0 has strangess S = +1

The total strangeness of the intermediate system is 0. The pion and proton do not carry strangeness and the total strangeness of the initial channel is thus also 0. **Strangeness is conserved in the strong interaction**.
If we look at the decay reaction that produces the pion and proton we see that strangeness is not conserved. We conclude that **strangeness is no conserved in weak interactions**.

Consider the following properties of some strange particles:

- The Λ^0 has a mass of 1116 MeV, very similar to the mass of the nucleon. There are no other particles in this mass range, and it thus must be a T = 0 particle and T_z = 0. It is a fermion and has spin ½. Its parity is even.
- The K comes in three forms: two kaons have charge (+e and –e) and one kaon is neutral. The mass of the charged kaons is 494 MeV and the mass of the neutral kaon is 498 MeV. The isospin properties of the kaon can be studied by considering the following reaction:

$$\underbrace{\pi^-}_{T=1} + \underbrace{p}_{T=1/2} \rightarrow \underbrace{\Lambda^0}_{T=0} + \underbrace{K^0}_{T=1/2 \text{ or } 3/2}$$

If $T = 3/2$, there would be four values of T_z and four possible charge states. Based on the known properties of the kaons, we can rule out this possibility. We thus conclude that the kaon must be a $T = ½$ particle. To determine the value of T_z of the kaon, we look at conservation of T_z:

$$\underbrace{\pi^-}_{T_z=-1} + \underbrace{p}_{T_z=1/2} \rightarrow \underbrace{\Lambda^0}_{T_z=0} + \underbrace{K^0}_{T_z=-1/2}$$

The neutral kaon has T_z = -½. The kaon with T_z = +½ is the kaon with a positive charge (K^+). The negative kaon has to be the anti-particle of the positive kaon.

Based on the observations, we have to modify the relation between charge and isospin in the following way:

$$Q = T_z + \frac{B+S}{2}$$

where S is the strangeness of the particle.

The properties of many other particles are shown in the table at the bottom of this page.

Table 17-1. Particles that are Stable or Decay either Weakly or Electromagnetically

Generic Name	Particle Symbol	Rest Mass (MeV/c^2)	Lifetime (sec)	Charge Q	Intrinsic Spin s	Lepton Number L_e, L_μ, or L_τ	Baryon Number B	Intrinsic Parity P	Isospin T	Isospin z component T_z	Strangeness S
Photon	γ	0	stable	0	1	0	0	Odd	0, 1	0	0
Leptons	ν_e	0	stable	0	1/2	+1	0				
	ν_μ	0	stable	0	1/2	+1	0				
	ν_τ	0	stable	0	1/2	+1	0				
	e^-	0.511	stable	−1	1/2	+1	0				
	μ^-	105.7	2.2×10^{-6}	−1	1/2	+1	0				
	τ^-	1784	5×10^{-13}	−1	1/2	+1	0				
Mesons	π^+	139.6	2.6×10^{-8}	+1	0	0	0	Odd	1	+1	0
	π^0	135.0	8×10^{-17}	0	0	0	0	Odd	1	0	0
	π^-	139.6	2.6×10^{-8}	−1	0	0	0	Odd	1	−1	0
	K^+	493.8	1.2×10^{-8}	+1	0	0	0	Odd	1/2	+1/2	+1
	K^0	497.8	8.9×10^{-11}	0	0	0	0	Odd	1/2	−1/2	+1
			and								
	$\overline{K^0}$	497.8	5.2×10^{-8}	0	0	0	0	Odd	1/2	+1/2	−1
	K^-	493.8	1.2×10^{-8}	−1	0	0	0	Odd	1/2	−1/2	−1
	η^0	549	8×10^{-19}	0	0	0	0	Odd	0	0	0
	η'	958	2×10^{-21}	0	0	0	0	Odd	0	0	0
Baryons	p	938.3	stable	+1	1/2	0	+1	Even	1/2	+1/2	0
	n	939.6	925	0	1/2	0	+1	Even	1/2	−1/2	0
	Λ^0	1116	2.6×10^{-10}	0	1/2	0	+1	Even	0	0	−1
	Σ^+	1189	8.0×10^{-11}	+1	1/2	0	+1	Even	1	+1	−1
	Σ^0	1192	6×10^{-20}	0	1/2	0	+1	Even	1	0	−1
	Σ^-	1197	1.5×10^{-10}	−1	1/2	0	+1	Even	1	−1	−1
	Ξ^0	1315	2.9×10^{-10}	0	1/2	0	+1	Even	1/2	+1/2	−2
	Ξ^-	1321	1.6×10^{-10}	−1	1/2	0	+1	Even	1/2	−1/2	−2
	Ω^-	1672	8.2×10^{-11}	−1	3/2	0	+1	Even	0	0	−3