## MODULE-6

- Characteristics of Fundamental Interactions
- Isospin invariance


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## PARTICLE PHYSICS(L6,L7)

## FUNDAMENTAL FORCES OF NATURE



## Characteristics of Fundamental Interactions:

Fundamental Interactions are classified into four types, namely

1. Strong Interaction
2. Weak Interaction
3. EM Interaction
4. Gravitational Interaction

- Exchange Particle
- Range
- Strength
- Time scale

|  | Strong Interaction | Weak Interaction | EM Interaction | Gravitational Interaction |
| :--- | :---: | :---: | :---: | :---: |
| Exchange Particle | Gluons $(g)$ | $W^{ \pm}, Z$ | Photon $(\gamma)$ | Graviton $(G)$ |
| Mass | 0 | $81 \mathrm{GeV}, 91 \mathrm{GeV}$ | 0 | 0 |
| Spin | 1 | 1 | 1 | 2 |

## Range of a Fundamental Interaction:

Interactions occur via exchange particles known as Mediating particle.
The de'Broglie's wavelength of the corresponding mediating particle determines the range of the particular type of interaction.
Assuming the mediating particle to be moving with velocity of light in the ultrarelativistic limit we obtain the following expression:

$$
\lambda=\frac{\hbar}{p} \approx \frac{\hbar}{m c}=\frac{\hbar c}{m c^{2}}
$$

For the sake of simplicity assume $\hbar c=200 \mathrm{MeV}-\mathrm{fm}$ instead of $197 \mathrm{MeV}-\mathrm{fm}$, one can estimate the range of an interaction from the above expression.
Range of any interaction is found to be inversely proportional to mass of the exchange particle.

## Range of Strong Interaction:

Assuming pion to be the exchange particle, the range can be estimated as follows

$$
\lambda_{S I}=\frac{\hbar c}{m_{\pi} c^{2}}=\frac{200 \mathrm{MeV}-\mathrm{fm}}{140 \mathrm{MeV}} \approx 1.4 \times 10^{-15} \mathrm{~m}
$$

This is the typical size of the diameter of a nucleus.

Range of Weak Interaction:
Mediators: $W^{ \pm}, Z$
Masses : $M_{W}=80 \mathrm{GeV} ; M_{Z}=91 \mathrm{GeV}$

$$
\lambda_{W I}=\frac{\hbar c}{m_{W} c^{2}}=\frac{200 \mathrm{MeV}-f m}{80 \mathrm{GeV}} \approx 2.5 \times 10^{-18} \mathrm{~m}
$$

## Range of EM Interaction:

## Mediator: Photon

Mass: $m_{\gamma}=0$ (Rest mass)

$$
\lambda_{E M I}=\frac{\hbar c}{m_{\gamma} c^{2}}=\infty
$$

Consistent with our daily observations.
Range of Gravitational Interaction:
Mediator : Graviton
Mass: $m_{G}=0$

$$
\lambda_{G I}=\frac{\hbar c}{m_{G} c^{2}}=\infty
$$

Conclusions:

- SI and WI are forces of short range.
- EMI and GI are forces of infinite range


## Strength of Fundamental Interactions:

The interaction can be classified according to the value of a characteristic dimensionless constant related through a coupling constant to the interaction cross section and interaction time. The stronger the interaction, the larger is the interaction cross section and shorter is the interaction time.
If the potential is defined as $V(r)=\frac{g}{r} e^{-\frac{r}{R}}$ where, $g$ is the coupling constant, $R$ is the range of the corresponding potential. Notice that this type of potentials are of finite range.
The dimensionless constant is $\frac{g^{2}}{\hbar c}$ estimates the strength of the corresponding interaction.
Strong Interaction:

$$
V_{s}(r)=\frac{g_{s}}{r} e^{-\frac{r}{R}}
$$

$g_{s}$ : Strong coupling constant
$R$ : Range of the SI $\left(10^{-15} \mathrm{~m}\right)$
dimensionless constant, $\frac{g_{s}^{2}}{\hbar c} \approx 1-10$

## Weak Interaction:

$$
V_{w}(r)=\frac{g_{w}}{r} e^{-\frac{r}{R}}
$$

$g_{w}$ : Strong coupling constant
$R$ : Range of the WI $\left(10^{-18} \mathrm{~m}\right)$
It is a short-range interaction, its strength is determined by the Fermi coupling constant for $\beta$-decay. $G_{F}=1.4 \times 10^{-49} \mathrm{erg}-\mathrm{cm}^{3}$
dimensionless constant, $\frac{g_{W}^{2}}{\hbar c}=\frac{G_{F} m_{p}^{2} c}{\hbar^{3}} \approx 10^{-5}$

## EM Interaction:

$$
V_{E M}(r)=\frac{e}{r}
$$

e: Electronic charge

## $R$ : Range of the EMI ( $\infty$ )

dimensionless constant, $\frac{e^{2}}{\hbar c} \approx \frac{1}{137} \approx 10^{-2} \quad \Rightarrow$ Fine structure constant, $\alpha$

Gravitational Interaction:

$$
V_{G I}(r)=\frac{G m_{p}}{r}
$$

$G m_{p}$ : Gravitational Strength parameter (assuming proton-proton interaction)
$R$ : Range of the EMI ( $\infty$ )
dimensionless constant, $\frac{G m_{p}^{2}}{\hbar c} \approx 6 \times 10^{-39}$

Conclusions:

- GI is the weakest interaction among the four fundamental interactions, hence it can be neglected in all particle interactions although its range is infinite.
- SI is the strongest among the four.
- Comparing the EMI with GI we see that $\frac{G m_{p}^{2}}{e^{2}} \approx 10^{-36}$ assuming protons to be the interaction particles.

Characteristic features of Four Fundamental Interactions

| Interaction | Characteristic <br> constant | Strength | Range of <br> Interaction | Typical Cross- <br> section | Typical <br> lifetime |
| :--- | :---: | :--- | :---: | :---: | :--- |
| Strong | $\frac{g_{s}^{2}}{\hbar c}$ | $1-10$ | $10^{-15} \mathrm{~m}$ | $10^{-26} \mathrm{~cm}^{2}$ | $10^{-23} \mathrm{~s}$ |
| Electromagnetic | $\frac{e^{2}}{\hbar c}$ | $10^{-2}$ | $\infty$ | $10^{-29} \mathrm{~cm}^{2}$ | $10^{-16} \mathrm{~s}$ |
| Weak | $\frac{g_{w}^{2}}{\hbar c}=\frac{G_{F} m_{p}^{2} c}{\hbar^{3}}$ | $10^{-5}$ | $10^{-18} \mathrm{~m}$ | $10^{-38} \mathrm{~cm}^{2}$ | $10^{-6}-10^{-10} \mathrm{~s}$ |
| Gravitational | $\frac{G m_{p}^{2}}{\hbar c}$ | $10^{-39}$ |  | $\infty$ |  |

Conservation Laws in Particle Physics:

| Interaction | E | P | J | Q | B | L | S | I | $I_{3}$ | II |
| :--- | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Strong | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y |
| Weak | Y | Y | Y | Y | Y | Y | N | N | N | N |
| EM | Y | Y | Y | Y | Y | Y | Y | N | Y | Y |

E: Energy
I : Isospin
P: Momentum
$I_{3}: 3^{\text {rd }}$ Component of isospin
J: Angular momentum
$\Pi$ : Parity
Q: Charge
L: Lepton no (more precisely, $L_{e}, L_{\mu}, L_{\tau}$ )
B: Baryon no
S Strangeness

## Relevant things to remember:

Gell-Mann-Nishijima Formula:

$$
Q=I_{3}+\frac{B+S}{2}
$$

$Y=B+S$ => Hypercharge,
Heperons: The particles having non-zero hypercharge quantum numbers are called Heperons.
e.g., $\Sigma^{ \pm, 0}, \Omega$ etc.

- Multiplicity of states (particles) determines the value of $I$
- Octet \& Decuplet give the information about $Q, B, S$ and quark content of particles.
- In determining whether a particular reaction is allowed or forbidden and also to determine the nature of a particular interaction, relevant quantum numbers are to be remembered with typical characteristics of the fundamental interactions.
- In order to check whether a particular reaction is allowed or not, Check with $E, P, J,($ normally conserved $) Q, B, L$
- In order to determine the nature of particular type of interaction, $S, I, I_{3}$ are to be checked in addition to the other quantum numbers mentioned above.

Eightfold Way

$$
s=1
$$



$$
\begin{aligned}
& s=0 \\
& s=-1
\end{aligned}
$$



$$
q=-1 \quad q=0
$$



Determination of $I_{3}$ for $p, n, \Sigma^{ \pm, 0}, \Lambda^{0}, \pi^{ \pm, 0}, \Omega^{-}$

$$
I_{3}=Q-\frac{B+S}{2}
$$

| For $p$ | For $n$ | For $\Lambda^{0}$ |  |
| :--- | :--- | :--- | :--- |
| $I_{3}=+1-\frac{1+0}{2}=+\frac{1}{2}$ | $I_{3}=0-\frac{1+0}{2}=-\frac{1}{2}$ | For $\Omega^{-}$ <br> $I_{3}=0$ |  |
| For $\Sigma^{ \pm, 0}$ | For $\pi^{ \pm, 0}$ | For $u$ |  |
| $I_{3}=+1-\frac{1-1}{2}=+1$ | $I_{3}=+1$ | $I_{3}=+\frac{2}{3}-\frac{\frac{1}{3}+0}{2}=+\frac{1}{2}$ | For $d$ |
| $I_{3}=-1-\frac{1-1}{2}=-1$ | $I_{3}=-1$ |  |  |
| $I_{3}=0-\frac{1-1}{2}=0$ | $I_{3}=0$ |  |  |

$$
\pi^{-}+p \rightarrow K^{+}+\Sigma^{-}
$$

## Allowed or Forbidden

$$
\begin{gathered}
\Delta Q=Q_{f}-Q_{i}=+1-1-(-1+1)=0 \\
\Delta B=B_{f}-B_{i}=0+1-(0+1)=0
\end{gathered}
$$

- Conservation of lepton number need not be checked as there is no lepton in this reaction.
- The reaction is possible
- If it is asked to find which law forbids this reaction then, conservation of $S, I_{3}, \Pi$ etc. are to checked.

Type of the Interaction: (Gell-Mann-Nishijima Formula needs to be used)

$$
\Delta I=I_{f}-I_{i}=\frac{1}{2}+1-\left(1+\frac{1}{2}\right)=0
$$

$$
\Delta I_{3}=I_{3 f}-I_{3 i}=+\frac{1}{2}-1-\left(-1+\frac{1}{2}\right)=0
$$

$$
\Delta S=S_{f}-S_{i}=+1-1-(0+0)=0
$$

It is a Strong Interaction. (Check from the Table in slide 11)

$$
\mu^{-} \rightarrow e^{-}+v_{\mu}+\overline{v_{e}}
$$

## Allowed or Forbidden

$$
\begin{gathered}
\Delta Q=Q_{f}-Q_{i}=-1+0+0-(-1)=0 \\
\Delta L_{\mu}=L_{\mu f}-L_{\mu i}=+1-(+1)=0 \\
\Delta L_{e}=L_{e f}-L_{e i}=-1+1-(0)=0
\end{gathered}
$$

- Conservation of baryon number need not be checked as there is no baryon in this reaction.
- The reaction is possible

$$
p+n \rightarrow \Lambda^{0}+\Sigma^{+}
$$

## Allowed or Forbidden

$$
\begin{gathered}
\Delta Q=Q_{f}-Q_{i}=0+1-(1+0)=0 \\
\Delta B=B_{f}-B_{i}=+1+1-(+1+1)=0
\end{gathered}
$$

- The reaction is possible
$n \rightarrow p+e^{-}$is forbidden due to violation of angular momentum \& Lepton no
$n \rightarrow p+\pi^{-}$is forbidden due to violation of energy conservation
$\pi^{0} \rightarrow \gamma+\gamma$ It is an em interaction
Why $p \rightarrow e^{+}+\pi^{0}$ decay is forbidden? Which conservation law forbids this decay?
$\Sigma^{+} \rightarrow p+\pi^{0}$
Here, $\Delta S=+1$, it is a Weak decay. Note that the particle that is decaying is strange one.


## PARTICLE PHYSICS(Lठ)



## Isospin:

In 1932 Heisenberg introduced the concept of isospin.
Masses of neutron and proton being nearly degenerate, Heisenberg proposed that neutrons and protons are the two states of a single particle called nucleon
$m_{p}=938.3 \mathrm{MeV} \& m_{n}=939.6 \mathrm{MeV}$
The small mass difference in mass might be due to electrostatic energy stored in proton as it is charged whereeas neutrons are neutral particles.

Isospin symmetry is like spin in ordinary space. Isospin symmetry is defined in internal space spanned by three axes represented by Pauli's matrices $\sigma_{x}, \sigma_{y}, \sigma_{z}$. It will follow the same algebra as spin does.
Rotational invariance in isospin space leads to conservation of Isospin.
Suppose we define a rotation in isospin space about axis-y by an amount $\theta$, the transformation is given by $U(\theta)=e^{i \sigma_{2} \theta}$
Define nucleon in two-component form : $N=\binom{\alpha}{\beta}$ with $\mathrm{p}=\binom{1}{0}$ and $\mathrm{n}=\binom{0}{1}$
Isospin is denoted by $\vec{I}$ which is a vector in an abstract isospin space having 3 components $I_{1}, I_{2}, I_{3}$

Like spin $3^{\text {rd }}$ component of isospin $\left(I_{3}\right)$ has values from $-I$ to $+I$ in steps of unity. (Multiplicity $=2 I+1$ )
The states of nucleon are :
$\left.\left.p=\left\lvert\, \frac{1}{2} \frac{1}{2}\right.\right\rceil \quad \mathrm{n}=\left\lvert\, \frac{1}{2}-\frac{1}{2}\right.\right\rceil$
The proton is "isospin up" and the neutron is "isospin down" just a convention.
Strong interaction is invariant under rotations in isospin space just like electrical forces are invariant under rotation in ordinary configuration spaces.
It is an "internal" symmetry as it has nothing to do with space-time but rather with the relations between different particles.

Example: A rotation through $180^{\circ}$ about axis- 1 in isospin space converts protons into neutrons, and vice versa. According to Noether's theorem, isospin is conserved in all strong interactions.

It is not an exact symmetry as there is small difference in masses of neutrons and protons.
Isospin is not conserved in electromagnetic interactions. Therefore, em interactions can differentiate neutrons and protons as the lattar are charged.

In the language of group theory, Heisenberg asserted that the strong interactions are invariant under an internal symmetry group $S U(2)$ and the nucleons belong to the two-dimensional representation (isospin $1 / 2$ ).

This is called nucleon isospin doublet.
Particles placed in a particular horizontal line in Eightfold Way diagrams belong to same multiplet with fixed isospin quantum number. Each member of the corresponding multiplet has different $I_{3}$ values.

$$
\begin{aligned}
& \text { For } \pi^{\prime} s: I=1 \text { (Triplet state, } 2 I+1=3 \text { ) } \\
& \pi^{+}=|11\rangle \quad \pi^{0}=|10\rangle \quad \pi^{-}=|1-1\rangle
\end{aligned}
$$

For $\Lambda, I=0($ Singlet $)$
$\Lambda=|00\rangle$
For $\Delta^{\prime} s, I=\frac{3}{2}$ (Quartet)
$\left.\Delta^{++}=\left\lvert\, \frac{3}{2} \frac{3}{2}\right.\right\rceil \quad \Delta^{+}=\left|\frac{3}{2} \frac{1}{2}\right\rangle \quad \Delta^{0}=\left|\frac{3}{2}-\frac{1}{2}\right| \quad \Delta^{-}=\left|\frac{3}{2}-\frac{3}{2}\right|$
Quark isospin doublet
$u=\left|\frac{1}{2} \frac{1}{2}\right\rangle \quad \mathrm{d}=\left|\frac{1}{2}-\frac{1}{2}\right|$

Nucleon-Nucleon scattering (Isopin is conserved)
(a) $p+p \rightarrow d+\pi^{+}$
(b) $p+n \rightarrow d+\pi^{0}$
(c) $n+n \rightarrow d+\pi^{-}$


Isospin of $d$ is 0 (Singlet)

## Initial States :

(a) $p+p:\left|\frac{1}{2} \frac{1}{2}\right\rangle\left|\frac{1}{2} \frac{1}{2}\right\rangle=|11\rangle$

## Final States:

(b) $p+n:\left|\frac{1}{2} \frac{1}{2}\right\rangle\left|\frac{1}{2}-\frac{1}{2}\right\rangle=\frac{1}{\sqrt{2}}|10\rangle+\frac{1}{\sqrt{2}}|00\rangle$
$d+\pi^{+}::|00\rangle|11\rangle=|11\rangle$
(c) $n+n:\left|\frac{1}{2}-\frac{1}{2}\right\rangle\left|\frac{1}{2}-\frac{1}{2}\right\rangle=|1-1\rangle$
$d+\pi^{0}::|00\rangle|10\rangle=|10\rangle$
$d+\pi^{-}::|00\rangle|1-1\rangle=|1-1\rangle$
Matrix element of process (a) : $\left\langle d \pi^{+}\right| \widehat{H}_{S I}|p p\rangle=\langle 11| \widehat{H}_{S I}|11\rangle=\langle 1| \widehat{H}_{S I}|1\rangle=M_{1}$
Matrix element of process (b) : $\left\langle d \pi^{0}\right| \widehat{H}_{S I}|p n\rangle=\frac{1}{\sqrt{2}}\langle 10| \widehat{H}_{S I}|10\rangle+\frac{1}{\sqrt{2}}\langle 10| \widehat{H}_{S I}|00\rangle=\frac{1}{\sqrt{2}}\langle 1| \widehat{H}_{S I}|1\rangle=\frac{M_{1}}{\sqrt{2}}$
Matrix element of process (c) : $\left\langle d \pi^{-}\right| \widehat{H}_{S I}|n n\rangle=\langle 1-1| \widehat{H}_{S I}|1-1\rangle=\langle 1| \widehat{H}_{S I}|1\rangle=M_{1}$
$\sigma_{a}: \sigma_{b}: \sigma_{c}=\left|M_{1}\right|^{2}: \frac{1}{2}\left|M_{1}\right|^{2}:\left|M_{1}\right|^{2}=2: 1: 2$

## Pion-Nucleon scattering:

(a) $\pi^{+}+p \rightarrow \pi^{+}+p$
(b) $\pi^{-}+p \rightarrow \pi^{-}+p$
(c) $\pi^{-}+p \rightarrow \pi^{0}+n$

## Initial/Final States :

$$
\begin{aligned}
& \pi^{+}+p:|11\rangle\left|\frac{1}{2} \frac{1}{2}\right\rangle=\left|\frac{3}{2} \frac{3}{2}\right\rangle \\
& \pi^{-}+p:|1-1\rangle\left|\frac{1}{2} \frac{1}{2}\right\rangle=\frac{1}{\sqrt{3}}\left|\frac{3}{2}-\frac{1}{2}\right\rangle-\sqrt{\frac{2}{3}}\left|\frac{1}{2}-\frac{1}{2}\right\rangle \\
& \pi^{0}+n:|10\rangle\left|\frac{1}{2}-\frac{1}{2}\right\rangle=\sqrt{\frac{2}{3}}\left|\frac{3}{2}-\frac{1}{2}\right\rangle+\frac{1}{\sqrt{3}}\left|\frac{1}{2}-\frac{1}{2}\right\rangle
\end{aligned}
$$



Matrix element of process (a) : $\left\langle\pi^{+} p\right| \widehat{H}_{S I}\left|\pi^{+} p\right\rangle=\left\langle\frac{3}{2} \frac{3}{2}\right| \widehat{H}_{S I}\left|\frac{3}{2} \frac{3}{2}\right\rangle=\left\langle\frac{3}{2}\right| \widehat{H}_{S I}\left|\frac{3}{2}\right\rangle=M_{3}$
Matrix element of process (b) : $\left\langle\pi^{-} p\right| \widehat{H}_{S I}\left|\pi^{-} p\right\rangle=\frac{1}{3}\left\langle\frac{3}{2}-\frac{1}{2}\right| \widehat{H}_{S I}\left|\frac{3}{2}-\frac{1}{2}\right\rangle+\frac{2}{3}\left\langle\frac{1}{2}-\frac{1}{2}\right| \widehat{H}_{S I}\left|\frac{1}{2}-\frac{1}{2}\right\rangle=$ $\frac{1}{3}\left\langle\frac{3}{2}\right| \widehat{H}_{S I}\left|\frac{3}{2}\right\rangle+\frac{2}{3}\left\langle\frac{1}{2}\right| \widehat{H}_{S I}\left|\frac{1}{2}\right\rangle=\frac{1}{3} M_{3}+\frac{2}{3} M_{1}$

Matrix element of process (b) : $\left\langle\pi^{-} p\right| \widehat{H}_{S I}\left|\pi^{-} p\right\rangle$
$=\frac{1}{3}\left\langle\frac{3}{2}-\frac{1}{2}\right| \widehat{H}_{S I}\left|\frac{3}{2}-\frac{1}{2}\right\rangle-\frac{\sqrt{2}}{3}\left\langle\frac{3}{2}-\frac{1}{2}\right| \widehat{H}_{S I}\left|\frac{1}{2}-\frac{1}{2}\right\rangle-\frac{\sqrt{2}}{3}\left\langle\frac{1}{2}-\frac{1}{2}\right| \widehat{H}_{S I}\left|\frac{3}{2}-\frac{1}{2}\right\rangle+\frac{2}{3}\left\langle\frac{1}{2}-\frac{1}{2}\right| \widehat{H}_{S I}\left|\frac{1}{2}-\frac{1}{2}\right\rangle$
$=\frac{1}{3}\left\langle\frac{3}{2}\right| \widehat{H}_{S I}\left|\frac{3}{2}\right\rangle+\frac{2}{3}\left\langle\frac{1}{2}\right| \widehat{H}_{S I}\left|\frac{1}{2}\right\rangle$
$=\frac{1}{3} M_{3}+\frac{2}{3} M_{1}$ where from orthogonality $\left\langle\frac{3}{2}-\frac{1}{2}\right| \widehat{H}_{S I}\left|\frac{1}{2}-\frac{1}{2}\right\rangle=\left|\frac{1}{2}-\frac{1}{2}\right| \widehat{H}_{S I}\left|\frac{3}{2}-\frac{1}{2}\right\rangle=0$
Matrix element of process (c) : $\left\langle\pi^{0} n\right| \widehat{H}_{S I}\left|\pi^{-} p\right\rangle$
$=\frac{\sqrt{2}}{3}\left\langle\frac{3}{2}-\frac{1}{2}\right| \widehat{H}_{S I}\left|\frac{3}{2}-\frac{1}{2}\right\rangle+\frac{1}{3}\left\langle\frac{3}{2}-\frac{1}{2}\right| \widehat{H}_{S I}\left|\frac{1}{2}-\frac{1}{2}\right\rangle-\frac{2}{3}\left\langle\frac{1}{2}-\frac{1}{2}\right| \widehat{H}_{S I}\left|\frac{3}{2}-\frac{1}{2}\right\rangle-\frac{\sqrt{2}}{3}\left\langle\frac{1}{2}-\frac{1}{2}\right| \widehat{H}_{S I}\left|\frac{1}{2}-\frac{1}{2}\right\rangle$
$=\frac{\sqrt{2}}{3}\left\langle\frac{3}{2}\right| \widehat{H}_{S I}\left|\frac{3}{2}\right\rangle-\frac{\sqrt{2}}{3}\left\langle\frac{1}{2}\right| \widehat{H}_{S I}\left|\frac{1}{2}\right\rangle$
$=\frac{\sqrt{ } 2}{3} M_{3}-\frac{\sqrt{ } 2}{3} M_{1}$
For $\Delta$ resonance $\left(I=\frac{3}{2}\right) M_{3} \gg M_{1}$ Therefore, $\sigma_{a}: \sigma_{b}: \sigma_{c}=\left|M_{3}\right|^{2}: \frac{1}{9}\left|M_{3}\right|^{2}: \frac{2}{9}\left|M_{3}\right|^{2}=9: 1: 2$
For $N^{*}$ resonance $\left(I=\frac{1}{2}\right) M_{1} \gg M_{3}$ Therefore, $\sigma_{a}: \sigma_{b}: \sigma_{c}=0: \frac{4}{9}\left|M_{1}\right|^{2}: \frac{2}{9}\left|M_{1}\right|^{2}=0: 2: 1$
$\Sigma^{0}(1915 \mathrm{MeV})$ is an electrically neutral baryon with $I=1, I_{3}=0$,
(a) $\Sigma^{0} \rightarrow \bar{K}^{0}+n \&(b) \Sigma^{0} \rightarrow K^{-}+p$ and estimate $\frac{\Gamma_{\bar{K}_{0} n}}{\Gamma_{K^{-}} p}$

Initial States :
$\Sigma^{0}:|10\rangle$

$$
\begin{array}{ll}
\bar{K}^{0}+n: & \left|\frac{1}{2} \frac{1}{2}\right\rangle\left|\frac{1}{2}-\frac{1}{2}\right\rangle=\frac{1}{\sqrt{2}}|10\rangle+\frac{1}{\sqrt{2}}|00\rangle \\
\mathrm{K}^{-}+p: & \left|\frac{1}{2}-\frac{1}{2}\right\rangle\left|\frac{1}{2} \frac{1}{2}\right\rangle=\frac{1}{\sqrt{2}}|10\rangle-\frac{1}{\sqrt{2}}|00\rangle
\end{array}
$$

$\left\langle\bar{K}^{0} n\right| \widehat{H}_{S I}\left|\Sigma^{0}\right\rangle=\frac{1}{\sqrt{2}}\langle 10| \widehat{H}_{S I}|10\rangle+\frac{1}{\sqrt{2}}\langle 00| \widehat{H}_{S I}|10\rangle=\frac{1}{\sqrt{2}}\langle 1| \widehat{H}_{S I}|1\rangle=\frac{1}{\sqrt{2}} M_{1}$
$\Gamma_{\bar{K}_{0} n} \alpha \frac{1}{2}\left|M_{1}\right|^{2}$
$\left\langle K^{-} p\right| \widehat{H}_{S I}\left|\Sigma^{0}\right\rangle=\frac{1}{\sqrt{2}}\langle 10| \widehat{H}_{S I}|10\rangle-\frac{1}{\sqrt{2}}\langle 00| \widehat{H}_{S I}|10\rangle=\frac{1}{\sqrt{2}}\langle 1| \widehat{H}_{S I}|1\rangle=\frac{1}{\sqrt{2}} M_{1}$
$\Gamma_{K^{-} p} \alpha \frac{1}{2}\left|M_{1}\right|^{2}$
Therefore, $\frac{\Gamma_{\bar{K}_{0} n}}{\Gamma_{K^{-}} p}=1$

