Introduction of Particle Physics
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Collapsar

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Contents

第 1 章

1.1 Elementary Particle Kinematic and Dynamics

1.1.1 Scale

- $$\left.\begin{aligned} Atom &: \sim 10^{-8}\text{cm} \\ Nucleon &: \sim 10^{-12}\text{cm} \\ Proton &: 0.8\times 10^{-14}\text{cm} \end{aligned}\right\} \textbf{Structure}$$

- $$Electron :< 10^{-16}\text{cm} \leftarrow \textbf{point particle}$$

1.1.2 Units

Natural units:

$$\hbar = c = 1 \Leftarrow \left\{\begin{aligned} &\hbar = 6.58211\times 10^{-15}\text{Gev}\cdot\text{Sec} \\ &c = 3\times 10^{10}\text{cm/Sec} \end{aligned}\right\} \Rightarrow \begin{aligned} &1\text{Gev} = (6.6\times 10^{-25}\text{Sec})^{-1} \approx 1.52\times 10^{24}\text{Sec}^{-1} \\ &1\text{Gev}^{-1} \approx 6.6\times 10^{-25}\text{s} \\ &1\text{Sec} = 3\times 10^{10}\text{cm} \end{aligned}$$

Dimension:

Dimension	Type		
M^0	velocity	angular momentum	
M^1	mass	energy	momentum
M^{-1}	length	time	
M^{-2}		cross section	

$$\begin{aligned} m_e = m_e c = m_e c^2 &\approx \frac{1}{2}\text{MeV} \\ &= \frac{1}{\hbar/m_e c} \approx (4\times 10^{-11}\text{cm})^{-1} \\ &= \frac{1}{\hbar/m_e c^2} \approx (1.3\times 10^{-21}\text{Sec})^{-1} \end{aligned}$$

Physical constants

$$G_F{}^{①} = 1.16637(2)\times 10^{-5}\text{GeV}^{-2}$$

$$M_{pl}{}^{②} = G_N^{-1/2} = M_{pl} = 1.2\times 10^{19}\text{GeV}$$

$$M_W = 80.41 \pm 0.10\text{GeV}$$

$$M_Z = 91.187 \pm 0.007\text{GeV}$$

$$M_e = 0.51099906(15)\text{MeV}$$

$$M_p{}^{③} = 938.2723(3)\text{MeV}$$

① *Fermi constant*

② *Planck mass*

③ *proton mass*

1.1.3 Kinematics

Mass

$$E = \frac{m}{\sqrt{1-v^2}}, \mathbf{p} = \frac{m\mathbf{v}}{\sqrt{1-v^2}} \Rightarrow E^2 - \mathbf{p}^2 = m^2, \tag{1.1.1}$$

here E is energy ,$\mathbf{P}$ is momentum,$\mathbf{v}$ is velocity,and m is rest mass.

Experiment unstable particle

Probability density is given by

$$\boxed{\rho(M) = \frac{\Gamma}{2\pi\left[(M-m)^2 + \frac{\Gamma^2}{4}\right]}} \tag{1.1.2}$$

Fig. 1.1.1 shows Breit-Wigner distribution,where m is the mass, Γ is the width.

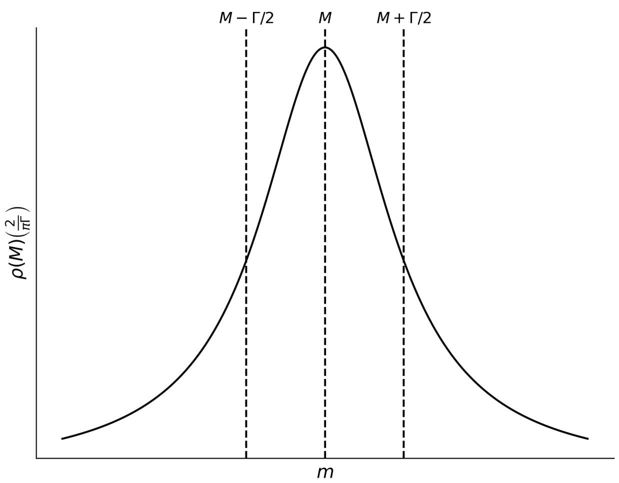

Figure 1.1.1. Breit-Wigner distribution

Lifetime,unstable particles——most of particles are unstable.

$$t \to t + \mathrm{d}t, N \to N - \mathrm{d}N$$
$$\mathrm{d}N = -\tau^{-1}N(t)\mathrm{d}t \Rightarrow N(t) = N(0)e^{-\frac{t}{\tau}},$$

here τ is lifetime and $\boxed{\tau = \frac{1}{\Gamma}}$.

Proof. **QM**
Consider a free particle with its wave function being $\psi(x,t)$

$$i\frac{\partial\psi(x,t)}{\partial t} = H\psi(x,t) \quad Schrödinger eq \tag{1.1.3}$$

Here H is Hamiltionian,which has eigenvalue E ——Energy.
The solution of $Schrödinger$ eq is

$$\psi(x,t) = e^{-iEt}\psi(x) \tag{1.1.4}$$

Normalization condition is

$$\int |\psi(x,t)|^2 \mathrm{d}^3 x = 1, \tag{1.1.5}$$

and $|\psi(x,t)|$ has the physical meaning of the probability density of the particle at time t and space x.
If E is real ,the probability fnding the particle is independent of time $|\psi(x,t)|^2 = |\psi(x)|$.
To introduce an exponential decay of a state ,a small imaginary part is added to the energy

$$E = m - \frac{1}{2} i\Gamma, \tag{1.1.6}$$

here m, Γ is real ,and the factor is chosen for convenience.Then we have

$$\psi(x,t) = e^{-i(m-\frac{1}{2}i\Gamma)t}\psi(x) = \psi(x)e^{-imt}e^{-\frac{\Gamma}{2}t} \Rightarrow |\psi(x,t)|^2 = |\psi(x)|^2 e^{-\Gamma t}. \tag{1.1.7}$$

At the same time ,we have

$$N(t) = N(0)e^{-\frac{t}{\tau}}, \tag{1.1.8}$$

then $\Gamma\tau = 1$.
Use Fourier transformation to descerbe the wave function in terms of energy instead of time.
Consider a function $f(x,t)$

$$\begin{aligned} f(x,t) &= \frac{1}{(2\pi)^{1/2}} \int_{-\infty}^{\infty} \mathrm{d}M g(x,M) \exp(-iMt) && (1.1.9) \\ g(x,M) &= \frac{1}{(2\pi)^{1/2}} \int_{-\infty}^{\infty} \mathrm{d}t f(x,t) \exp(+iMt) \xlongequal[t<0,\psi(x,t)=0]{f(x,t)=\psi(x,t)} && (1.1.10) \\ &\frac{1}{(2\pi)^{1/2}} \int_{0}^{\infty} \mathrm{d}t \psi(x) \exp\left(i(M-m+\frac{1}{2}i\Gamma)t\right) && (1.1.11) \\ &= \frac{\psi(x)}{(2\pi)^{1/2}} \frac{i}{M-m+i\Gamma/2}. && (1.1.12) \end{aligned}$$

The probability density $\rho(M)$ of finding the particle with mass M

$$\rho(M) = c\int \mathrm{d}^3 x |g(g,M)|^2 \xlongequal{\int \mathrm{d}^3 x\psi(x) = 1} \frac{c}{2\pi}\frac{1}{(M-m)^2} + \frac{\Gamma^2}{4} = \frac{\Gamma}{2\pi}\frac{1}{(M-m)^2 + \Gamma^2/4}, \tag{1.1.13}$$

where we use the formula

$$\int_{\infty}^{\infty} f(M) dM = 1 \Rightarrow C = \Gamma. \tag{1.1.14}$$

The measurement on the mass of unstable parcels is uncertain

$$\tau\Gamma = 1 \longrightarrow \tau\Gamma = h \quad (\Delta t \Delta E \geqslant \hbar). \tag{1.1.15}$$

.... □

Some common particles have the following masses,

- photon: $\tau_\gamma = \infty$

- electron: $\tau > 2 \times 10^{23}$yr
- muon: $\tau = 2.19703(4) \times 10^{-6}$ s
- $\pi^{\pm} : \tau = 26029(23) \times 10^{-8}$ s
- $\pi^{0} : \tau = (84 \pm 06) \times 10^{-17}$ s
- N : $\tau = (896 \pm 10)$s
- Proton: $\tau > 10^{32} y_r$

Electric charge

$$e = 1.60217733(49) \times 10^{-11}\text{C}$$

$$\frac{|q_p| - |q_e|}{|q_e|} < 10^{-21} \qquad \leftarrow |q_n| = |q_p| = |q_e| \Rightarrow q_n = 0$$

Why the electric charge of particle is quantized?

Spin

- $Fermon : 1/2, 3/2, 5/2, \cdots$
- $Boson : 0, 1, 2, \cdots$

The spins of common particles are as follows:

Example	H	γ	e	μ	π	p	n	W	Z
Spin	0	1	1/2	1/2	0	1/2	1/2	1	1

Table 1.1. The spins of common particles

1.1.4 Particle classification

In the standard model

(1). Gauge bosons: $\gamma, W^{\pm}, Z$,g(8 gluons) ——Spin 1
(2). Scale boson: Higgs boson H ——Spin=0
(3). Fermions: leptons + quarks ——Spin =1/2

Leptons:

l	Q	l_e	l_μ	l_τ
e	-1	1	0	0
ν_e	0	1	0	0
μ	-1	0	1	0
ν_μ	0	0	1	0
τ	-1	0	0	1
ν_τ	0	0	0	1

Table 1.2. Lepton Table

There are also six antileptons with all the signs reversed position $Q = 1, l_e = -1$.
Lepton are conserved!

$$\underset{1}{e^-} + \underset{1}{e^+} \not\rightarrow \underset{0}{\pi^+} + \underset{0}{\pi^-}$$

Quarks:

q	Q	B
d	$-1/3$	1/3
u	$2/3$	1/3
s	-1/3	1/3
c	2/3	1/3
b	-1/3	1/3
t	2/3	1/3

Table 1.3. Quark Charges and Baryon Numbers

Here B=Baryon,which is also conserved.

$$\underset{1}{p} \not\to \underset{0}{e^+} + \underset{0}{\pi^0}$$

Observed particles

(1). Gauge bosons: $\gamma, W^{\pm}, Z$
(2). Leptons:$e, \mu, \tau, \nu_e, \nu_\mu, \nu_\tau$
(3). Hadrons (强子,strong interaction)

- Mesons(介子):spin=$0, 1, \cdots$, B=0
- Bargons(重子):spin=$1/2, 3/2$, B=1