Appendix A

A.1 Relativistic Kinematics

If the space coordinates x, y, z and the time coordinate t are measured in the laboratory frame Σ and the corresponding coordinates x^*, y^*, z^* and t^* in a different frame Σ moving say along the x-axis with velocity βc, then

$$\sum_{i=1}^{4} x_i^2 = \sum_{i=1}^{4} x_i^{*2} = \text{constant} \tag{A.1}$$

where we have written

$$x = x_1, \qquad y = x_2, \qquad z = x_3, \qquad ict = x_4$$

The x_i are the components of a Lorentz invariant four-vector.

One of the most useful four-vectors is that formed by the energy and the three components of the momentum. Thus, $(p_x, p_y, p_z, iE) = (p, iE)$ is a Lorentz-invariant four-vector and

$$\left(\sum E\right)^2 - \left|\sum p\right|^2 = \left(\sum E^*\right)^2 \tag{A.2}$$

since $\sum p^* = 0$ in the center of mass.

A.2 Expressions for Production Threshold

Let a particle of mass m_1, moving with velocity βc with kinetic energy T_1 hit a stationary nucleon of mass m_2 and barely produce particles of mass m_3 and m_4. Then using (A.2) in natural units

$$\begin{aligned} &(T_1 + m_1 + m_2)^2 - p_1^2 = (m_3 + m_4)^2 \quad \text{or} \\ &(T_1 + m_1 + m_2)^2 - \left(T_1^2 + 2m_1T_1\right) = (m_3 + m_4)^2 \\ &T_1 = \frac{1}{2m_2}\left[(m_3 + m_4)^2 - (m_1 + m_2)^2\right] \end{aligned} \tag{A.3}$$

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A.3 Expressions for γ_c and γ^*

Let a particle of mass m_1, velocity β and Lorentz factor $\gamma = (1-\beta^2)^{-1/2}$ be incident on another particle of mass m_2 at rest. Let the CMS have Lorentz factor γ_c. Let m_1 be moving with velocity β^* in the CMS. m_2 will be moving with velocity β_c, in a direction opposite to that of m_1. By definition, the total momentum in the CMS before and after the collision is zero.

$$m_1\gamma^*\beta^* = m_2\gamma_c\beta_c \tag{A.4}$$

Squaring (A.4) and expressing β in terms of γ,

$$m_1^2\left(\gamma^{*2}-1\right) = m_2^2\left(\gamma_c^2-1\right) \tag{A.5}$$

Using the invariance (A.2)

$$(m_1\gamma + m_2)^2 - m_1^2\left(\gamma^2-1\right) = \left(m_1\gamma^* + m_2\gamma_c\right)^2 \tag{A.6}$$

Combining (A.5) and (A.6) and calling $\nu = \frac{m_2}{m_1}$,

$$\gamma_c = \frac{\gamma+\nu}{\sqrt{1+2\gamma\nu+\nu^2}} \tag{A.7}$$

$$\gamma^* = \frac{\gamma+\frac{1}{\nu}}{\sqrt{1+\frac{2\gamma}{\nu}+\frac{1}{\nu^2}}} \tag{A.8}$$

For the special case, $m_1 = m_2$, as in p–p collision

$$\gamma_c = \gamma^* = \sqrt{\frac{\gamma+1}{2}} \tag{A.9}$$

For $\gamma \gg 1$,

$$\gamma_c \simeq \sqrt{\frac{\gamma}{2}} \tag{A.10}$$

A.4 Relation Between Lab and CMS Angles

The Lorentz transformations are:

$$E^* = Vc(E - \beta_c p\cos\theta) \tag{A.11}$$

$$p^*\cos\theta^* = \gamma_c(p\cos\theta - \beta_c E) \tag{A.12}$$

$$p^*\sin\theta^* = p\sin\theta \tag{A.13}$$

$$E = \gamma_c\left(E^* + \beta_c p^*\cos\theta^*\right) \tag{A.14}$$

$$p\cos\theta = \gamma_c\left(p^*\cos\theta^* + \beta_c E^*\right) \tag{A.15}$$

Combining (A.13) and (A.15)

$$\tan\theta = \frac{1}{\gamma_c}\frac{p^*\sin\theta^*}{p^*\cos\theta^* + \beta_c E^*} = \frac{1}{\gamma_c}\frac{\sin\theta^*}{(\cos\theta^* + \frac{\beta_c}{\beta^*})}$$

$$\left(\because \frac{p^*}{E^*} = \beta^*\right) \tag{A.16}$$

The inverse transformation of angles is

$$\tan\theta^* = \frac{\sin\theta}{r_c(\cos\theta - \frac{\beta_c}{\beta})} \tag{A.17}$$

Appendix B

B.1 Composition of Angular Momenta and the Clebsch Gordon Coefficients

The combination of two angular momenta $|I_1 m_1\rangle$ and $|I_2 m_2\rangle$ to form a total angular momentum $|JM\rangle$ must obey the following selection rules:

$$|j_1 - j_2| \leq J \leq j_1 + j_2 \tag{B.1}$$

$$M = m_1 + m_2 \tag{B.2}$$

$$J \geq |M| \tag{B.3}$$

The coupled states may be expanded with the aid of the Clebsch Gordon coefficients (CGC) $(j_1 j_2 m_1 m_2 | JM)$ in the $|j_1 j_2 JM\rangle$ basis:

$$M = m_1 + m_2$$

The weights of various allowed j-values contributing to the two-particle state are given by

$$\varphi_1(j_1 m_1)\varphi_2(j_2 m_2) = \sum_j c_j \psi(j, m) \tag{B.4}$$

The C_j's are known as Clebsch-Gordan coefficients (or Wigner coefficients).

The probability that the combination of two angular momenta $|j_1 m_1\rangle$ and $|j_2 m_2\rangle$ produces a system with total angular momentum $|JM\rangle$ is thus the square of the corresponding CGC's.

Equation (B.4) may also be applied to isospin. We list below three combinations of j_1 and j_2 which have been used in the book. The sign convention in the tables follows that of Condon and Shortley [1].

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$\frac{1}{2} \times \frac{1}{2}$

	J	1	1	0	1
	M	$+1$	0	0	-1
m_1	m_2				
$+\frac{1}{2}$	$+\frac{1}{2}$	1			
$+\frac{1}{2}$	$-\frac{1}{2}$		$\sqrt{\frac{1}{2}}$	$\sqrt{\frac{1}{2}}$	
$-\frac{1}{2}$	$+\frac{1}{2}$		$\sqrt{\frac{1}{2}}$	$-\sqrt{\frac{1}{2}}$	
$-\frac{1}{2}$	$-\frac{1}{2}$				1

$1 \times \frac{1}{2}$

	J	$\frac{3}{2}$	$\frac{3}{2}$	$\frac{1}{2}$	$\frac{3}{2}$	$\frac{1}{2}$	$\frac{3}{2}$
	M	$+\frac{3}{2}$	$+\frac{1}{2}$	$+\frac{1}{2}$	$-\frac{1}{2}$	$-\frac{1}{2}$	$-\frac{3}{2}$
m_1	m_2						
$+1$	$+\frac{1}{2}$	1					
$+1$	$-\frac{1}{2}$		$\sqrt{\frac{1}{3}}$	$\sqrt{\frac{2}{3}}$			
0	$+\frac{1}{2}$		$\sqrt{\frac{2}{3}}$	$-\sqrt{\frac{1}{3}}$			
0	$-\frac{1}{2}$				$\sqrt{\frac{2}{3}}$	$\sqrt{\frac{1}{3}}$	1
-1	$+\frac{1}{2}$				$\sqrt{\frac{1}{3}}$	$-\sqrt{\frac{2}{3}}$	
-1	$-\frac{1}{2}$						1

1×1

	J	2	2	1	2	1	0	2	1	2
	M	$+2$	$+1$	$+1$	0	0	0	-1	-1	-2
m_1	m_2									
$+1$	$+1$	1								
$+1$	0		$\sqrt{\frac{1}{2}}$	$\sqrt{\frac{1}{2}}$						
0	$+1$		$\sqrt{\frac{1}{2}}$	$-\sqrt{\frac{1}{2}}$						
$+1$	-1				$\sqrt{\frac{1}{6}}$	$\sqrt{\frac{1}{2}}$	$\sqrt{\frac{1}{3}}$			
0	0				$\sqrt{\frac{2}{3}}$	0	$-\sqrt{\frac{1}{3}}$			
-1	$+1$				$\sqrt{\frac{1}{6}}$	$-\sqrt{\frac{1}{2}}$	$\sqrt{\frac{1}{3}}$			
0	-1							$\sqrt{\frac{1}{2}}$	$\sqrt{\frac{1}{2}}$	
								$\sqrt{\frac{1}{2}}$	$-\sqrt{\frac{1}{2}}$	
-1	-1									1

References

1. Condon, Shortley (1951)

Appendix C

C.1 Special Functions

C.1.1 Bessel Functions

The Bessel functions are solutions of a differential equation of the form

$$\nabla^2\varphi + B^2\varphi = 0 \tag{C.1}$$

where cylindrical coordinates are used.

Bessel's ordinary differential equation is

$$x^2\frac{d^2y}{dx^2} + x\frac{dy}{dx} + \left(x^2 - n^2\right)y = 0 \tag{C.2}$$

where the constant n is the order of the equation. The two solutions, obtained by series methods, are

$J_n(x)$ first kind
$Y_n(x)$ second kind

$$J_n(x) = \sum_{K=0}^{\infty}\frac{(-1)^K(\frac{x}{2})^{n+2K}}{K!(n+K)!} \tag{C.3}$$

It converges for all finite values of x.

A second solution of Bessels equation is obtained as $J_n(x)\ln x$ plus a new series in x called $Y_n(x)$. Note that $Y_n(x)$ diverges for $x = 0$ and therefore cannot be a solution in physical problems.

The most frequently encountered orders are the zero ($n = 0$) and first ($n = 1$). Figure C.1 shows $J_0(x)$ and $J_1(x)$; Fig. C.2 shows $Y_0(x)$ and $Y_1(x)$.

Bessel functions when n is half an odd integer.

$$J_{1/2}(x) = \sqrt{\frac{2}{\pi x}}\sin x \tag{C.4}$$

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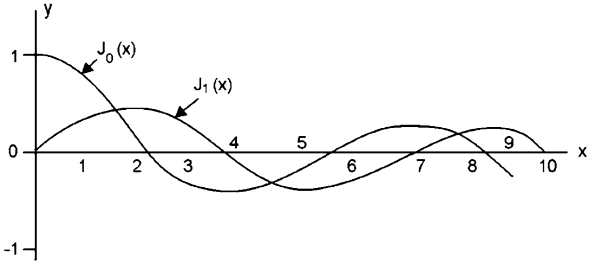

Fig. C.1 First kind of solutions $J_0(x)$ and $J_1(x)$ obtained by series method

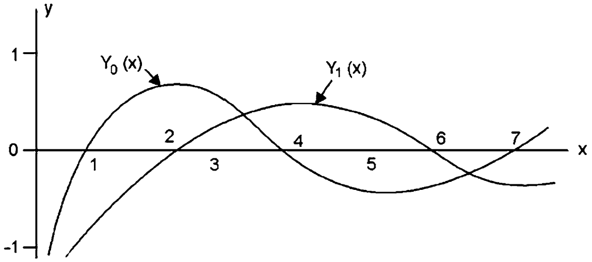

Fig. C.2 Second kind of solutions $Y_0(x)$ and $Y_1(x)$ obtained by series method

$$J_{-1/2}(x) = \sqrt{\frac{2}{\pi x}} \cos x \tag{C.5}$$

$$J_{3/2}(x) = \sqrt{\frac{2}{\pi x}} \left(\frac{\sin x}{x} - \cos x \right) \tag{C.6}$$

$$J_{-3/2}(x) = -\sqrt{\frac{2}{\pi x}} \left(\frac{\cos x}{x} + \sin x \right) \tag{C.7}$$

C.1.2 Asymptotic Expressions

$$J_{l+\frac{1}{2}}(x) = \sqrt{\frac{2}{\pi}} \frac{x^{l+\frac{1}{2}}}{(2l+1)!!} \quad x \ll 1 \tag{C.8}$$

$$J_{l+\frac{1}{2}}(x) = \sqrt{\frac{2}{\pi x}} \sin\left(x - \frac{\pi l}{2} \right) \quad x \gg 1 \tag{C.9}$$

C.1.3 Spherical Bessel Functions

The spherical Bessel functions are the solutions of the equation

$$x^2 \frac{d^2 y}{dx^2} + 2x \frac{dy}{dx} + \left[x^2 - l(l+1) \right] y = 0 \tag{C.10}$$

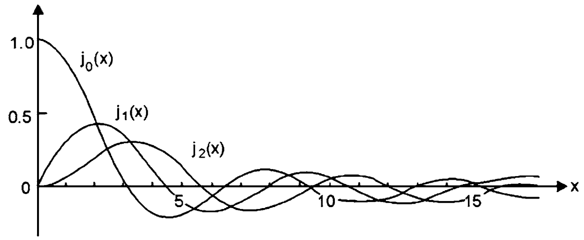

Fig. C.3 Curves for the first three j's of an ordinary Bessel function

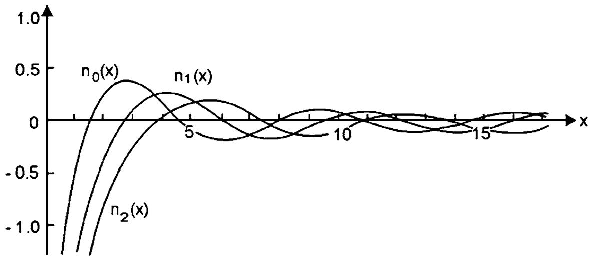

Fig. C.4 Spherical Bessel and Neumann functions for $j = 0.12$

The spherical Bessel function $j_l(x)$ which is regular at $x = 0$ is defined by

$$j_l(x) = \sqrt{\frac{\pi}{2x}} J_{l+\frac{1}{2}}(x) \tag{C.11}$$

where J is an ordinary Bessel function of half-odd integral order. Explicit expressions for the first three j's are

$$j_0(x) = \frac{\sin x}{x} \tag{C.12}$$

$$j_1(x) = \frac{\sin x}{x^2} - \frac{\cos x}{x} \tag{C.13}$$

$$j_2(x) = \left(\frac{3}{x^3} - \frac{1}{x}\right) \sin x - \frac{3}{x^2} \cos x \tag{C.14}$$

and the corresponding curves are shown in Fig. C.3.

Spherical Bessel and Neumann functions for different values of J are shown in Fig. C.4.

C.1.4 Spherical Harmonics

The angular part $Y_{lm}(\theta, \varphi)$ of the complete wave function, which is a solution of equation

$$\frac{1}{\sin\theta} \frac{\partial}{\partial\theta}\left(\sin\theta \frac{\partial Y}{\partial\theta}\right) + \frac{1}{\sin^2\theta} \frac{\partial^2 Y}{\partial\varphi^2} + \lambda Y = 0 \tag{C.15}$$

where $\lambda = l(l+1)$, is called a spherical harmonic. $Y_{lm}(\theta, \varphi)$ is related to the associated Legendre functions by

$$Y_{lm}(\theta, \varphi) = N_{lm} p_l^m(\cos\theta) f_m(\varphi) \tag{C.16}$$

where $f_m(\varphi)$ is given by

$$f_m(\varphi) = \frac{1}{\sqrt{2}\pi} e^{im\varphi} \tag{C.17}$$

and N_{em} is the normalization constant.

The normalized spherical harmonics are

$$Y_{lm}(\theta, \varphi) = \left[\frac{2l+1}{4\pi} \frac{(l-|m|)}{(l+|m|)}! \right]^{1/2} p_l^m(\cos\theta) e^{im\varphi} \tag{C.18}$$

The first four spherical harmonics are

$$\begin{aligned} Y_{0,0} &= \frac{1}{(4\pi)^{1/2}}, \qquad Y_{1,1} = \left(\frac{3}{8\pi} \right)^{1/2} \sin\theta e^{i\varphi} \\ Y_{1,0} &= \left(\frac{3}{4\pi} \right)^{1/2} \cos\theta, \qquad Y_{1,-1} = \left(\frac{3}{8\pi} \right)^{1/2} \sin\theta e^{-i\varphi} \end{aligned} \tag{C.19}$$

C.1.5 Associated Legendre Functions

Consider the equation

$$\frac{d}{dx}\left[\left(1-x^2\right) \frac{d}{dx} p_l^m(x) \right] + \left[l(l+1) - \frac{m^2}{1-x^2} \right] p_l^m(x) = 0 \tag{C.20}$$

$P_l^m(x)$ is called the associated Legendre function.

C.1.6 Ortho-normal Properties

$$\int_{-1}^{1} P_l^m(x) P_{l'}^m(x) dx = \frac{2}{2l+1} \frac{(l+m)!}{(l-m)!} \delta_{l'l} \tag{C.21}$$

where $\delta_{l'l} = 1$ if $l = l'$ and $= 0$ if $l \neq l'$.

Also,

$$P_l^{-m}(x) = (-1)^m \frac{(l-m)!}{(l+m)!} P_l^m(x) \tag{C.22}$$

Parity operation on spherical harmonics.

$$\begin{aligned} PY_{lm}(\theta, \varphi) &\sim PP_l^m(\cos\theta) e^{im\varphi} \\ &= (-1)^{l+m} P_l^m(\cos\theta)(-1)^m e^{im\varphi} \\ &= (-1)^{2m}(-1)^l Y_{lm}(\theta, \varphi) = (-1)^l Y_{lm}(\theta, \varphi) \end{aligned} \tag{C.23}$$

Appendix D

D.1 Table of Physical Constants

Constant	Symbol	Value
Speed of light	c	$2.998 \times 10^{8}\ \mathrm{m\,s^{-1}}$
permeability of vacuum	μ_0	$4\pi \times 10^{-7}\ \mathrm{H\,m^{-1}}$
permittivity of vacuum	$\epsilon_0 = 1/\mu_0 c^2$	$8.854 \times 10^{-12}\ \mathrm{F\,m^{-1}}$
elementary charge	e	$1.602 \times 10^{-19}\ \mathrm{C}$
gravitational constant	G	$6.673 \times 10^{-11}\ \mathrm{N\,m^2\,kg^{-2}}$
Atomic mass unit	u	$1.661 \times 10^{-27}\ \mathrm{kg}$
Mass		
of electron	m_e	$9.109 \times 10^{-31}\ \mathrm{kg}$
of proton	m_p	$1.673 \times 10^{-27}\ \mathrm{kg}$
of neutron	m_n	$1.675 \times 10^{-27}\ \mathrm{kg}$
energy equivalence of mass		
of electron	$m_e c^2$	0.511 MeV
of proton	$m_p c^2$	938.272 MeV
of neutron	$m_n c^2$	939.566 MeV
Planck constant	h	$6.626 \times 10^{-34}\ \mathrm{J\,s}$
$h/2\pi$	$\hbar$	$1.055 \times 10^{-34}\ \mathrm{J\,s}$
fine structure constant	$\alpha = e^2/4\pi\epsilon_0\hbar c$	7.297×10^{-3}
Bohr magneton	$\mu_B = e\hbar/2m_e$	$9.274 \times 10^{-24}\ \mathrm{J\,T^{-1}}$
nuclear magneton	$\mu_N = eh/2m_p$	$5.051 \times 10^{-27}\ \mathrm{J\,T^{-1}}$

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Constant	Symbol	Value
magnetic moment of		
electron	μ_e	$9.285 \times 10^{-24}\ \mathrm{J\,T^{-1}}$
of proton	μ_p	$1.411 \times 10^{-26}\ \mathrm{J\,T^{-1}}$ $= 2.793\mu_N$
of neutron	μ_n	$-0.966 \times 10^{-26}\ \mathrm{J\,T^{-1}}$ $= -1.913\mu_N$
electronvolt	eV	1.602×10^{-19} J
	keV $= 10^3$ eV	1.602×10^{-16} J
	MeV $= 10^6$ eV	1.602×10^{-13} J
	GeV $= 10^9$ eV	1.602×10^{-10} J
	TeV $= 10^{12}$ eV	1.602×10^{-7} J
barn	b	$10^{-28}\ \mathrm{m}^2$
	mb $= 10^{-3}$ b	$10^{-31}\ \mathrm{m}^2$
	μb $= 10^{-6}$ b	$10^{-34}\ \mathrm{m}^2$
	nb $= 10^{-9}$ b	$10^{-37}\ \mathrm{m}^2$

Appendix E

E.1 Dalitz Plots

E.1.1 Three Similar Particles

A convenient way of representing the three-body decay is due to Dalitz [1]. The original Dalitz plot was introduced for the decay

$$K^+ \to \pi^+ + \pi^+ + \pi^-, \qquad Q = 75 \text{ MeV} = \text{total kinetic energy}.$$

In this case the three particles have equal mass and are nearly non-relativistic. The plot is made of the kinetic energies of the pions along three axes at 120°, as in Fig. E.1.

All the points within the equilateral triangle have the property that the sum of the perpendicular distances from the three sides is a constant equal to the height of the triangle. One therefore draws an equilateral triangle of height Q and for each observed decay a point is marked which has perpendicular distances of the three sides equal to the kinetic energies of the three pions. All decays have points which lie within a region slightly smaller than the inscribed circle (due to relativistic effects), because of momentum conservation. The interval $dE_1 dE_2$ has an area which is independent of its position within the circle and it follows that the density points will be uniform if the matrix element is independent of the energy division.

Due to the symmetry of the decay all the experimental points can be plotted on a half circle. The plot gives information on the spin of K-meson. As it is for a weak decay no information is obtained for the parity of K-meson. On the other hand for a three-body decay by strong interaction, as for the ω, Dalitz plot gives information for both spin and parity, as discussed later in section Phase Space.

A statistical study of many such decays in which one measures the energies of pions and the angles between the trajectories leads to important conclusions.

The three particles emitted may have any momentum and energy permitted by the conservation laws. The largest energy carried by one of the particles, say π^- is

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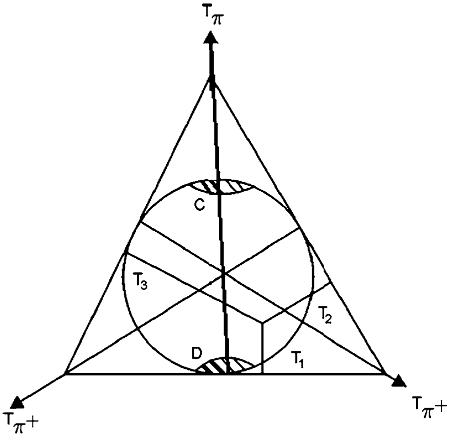


Fig. E.1 Plot of kinetic energies of the pions along three axes at 120°

when the other two pions travel in the opposite direction. It is easy to show that the maximum energy of π^- is $E_0 = (2/3)Q$, where $Q = (m_K - 3m_\pi)c^2$ obviously in the rest frame of K-meson, $E_1 + E_2 + E_3 = m_K C^2$.

The decay rate is governed by the golden rule

$$W = \frac{2\pi}{h} |M_{if}|^2 \delta(P_i - P_f) \frac{dN}{dE} \tag{E.1}$$

where the matrix element may be a function of the decay pions, the four-momenta delta function ensures energy and momentum conservation, and the last factor density of final states may be calculated separately.

Kinematic Limits The conservation of energy can be satisfied for all points within the triangle. However, the conservation of momentum imposes severe limit on the allowed region. For the non-relativistic case this limit is the inscribed circle which can be proved as follows.

$$\vec{p}_1 + \vec{p}_2 + \vec{p}_3 = 0 \tag{E.2}$$

Letting $\vec{p}_1$ and $\vec{p}_2$ in the same direction,

$$(p_1 + p_2)^2 = p_3^2 \tag{E.3}$$

But

$$p_1^2 = 2E_1 m, \qquad p_2^2 = 2E_2 m, \qquad p_3^2 = 2E_3 m \tag{E.4}$$

Using (E.4) in (E.3) and simplifying

$$E_1^2 + E_2^2 + E_3^2 - 2(E_1E_2 + E_2E_3 + E_3E_1) = 0 \tag{E.5}$$

which is an inscribed circle

$$x^2 + \left(y - \frac{E_1 + E_2 + E_3}{3}\right)^2 = \left(\frac{E_1 + E_2 + E_3}{3}\right)^2 \tag{E.6}$$

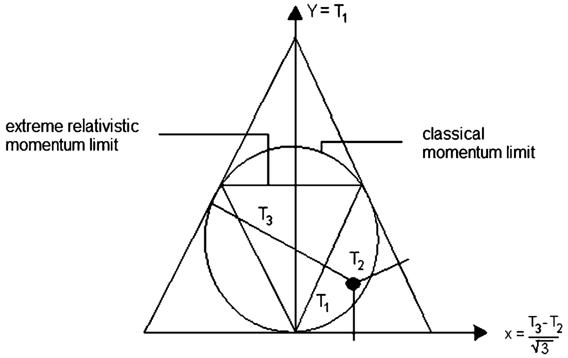


Fig. E.2 Relativistic and non-relativistic limits imposed by conservation of momentum

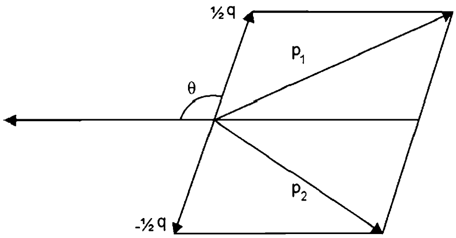


Fig. E.3 Relative momentum of the three particles

if we put $x = \frac{(E_3 - E_2)}{\sqrt{3}}$ and $y = E_1$, Fig. E.2.

In the relativistic case we get a triangle as shown in Fig. E.2. For intermediate cases we get a shape between these extremes.

We may note other features. Let two particles have relative momentum $\vec{q}$, and with respect to which the third particle has momentum $\vec{P}$, then we have the configuration as in Fig. E.3. $\vec{P} \cdot \vec{P}$ and $-\vec{P}$ are then the momenta in the overall CMS. θ is the angle between $\vec{p}$ and $\vec{q}$ so that $\cos\theta = (\vec{p} \cdot \overline{q})/pq$, Fig. E.3.

It may be verified that

$$\begin{aligned} P^2 &\propto PN \\ q^2 &\propto PQ \\ \cos\theta &= \frac{GP}{GH} \end{aligned} \tag{E.7}$$

where P, N, Q, G, H are as in Fig. E.4.

Phase-Space We shall now show that the energy density is proportional to dE_1, dE_2 for all the accessible regions of phase space, E_3 being determined once E_1 and E_2 are given.

The number of quantum states available in phase, per unit normalized volume, is

$$\frac{p^2 dp d\Omega}{\hbar^3}$$

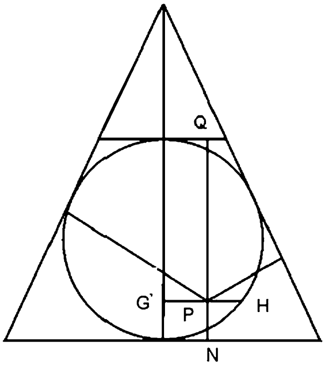


Fig. E.4 Dalitz plot for the three particles

for a spinless particle of momentum between p and $p + dp$ within the solid angle element $d\Omega$. In a reaction with a 3-body break-up into particles labeled 1, 2 and 3, and fixed initial energy, the number of states will be proportional to

$$p_1^2 dp_1 p_2^2 dp_2 d\Omega_1 d\Omega_2$$

There is no factor for particle 3 as in the CMS, $\vec{p}_3 = -(\vec{p}_1 + \vec{p}_2)$ is fixed. If the initial state is unpolarised the particle will be emitted isotropically. The integral over all directions of particle 1 is then $\int d\Omega_1 = 4\pi$, while $d\Omega_2 = 2\pi d(\cos\theta_{12})$, where θ_{12} is the angle between particle 1 and 2. Thus, the number of states in the element $dp_1 dp_2 d(\cos\theta_{12})$ is

$$dN = \text{const}\, p_1^2 dp_1 p_2^2 dp_2 d(\cos\theta_{12})$$

The phase space expression can be made relativistically invariant by including a factor of m/E or $1/E$ for each final state particle, where E in the total energy of the particle. The form is then

$$dN = \text{const}\, \frac{p_1^2 dp_1 p_2^2 dp_2 d(\cos\theta_{12})}{E_1 E_2 E_3}$$

Using the relations

$$\begin{aligned} E_1^2 &= p_1^2 + m_1^2, \qquad E_2^2 = p_2^2 + m_2^2 \\ E_3^2 &= p_3^2 + m_3^2 = p_1^2 + p_2^2 + 2p_1 p_2 \cos\theta + m_3^2 \\ E_1 dE_1 &= p_1 dp_1, \qquad E_2 dE_2 = p_2 dp_2 \\ (E_3 dE_3)_{p_1, p_2 fixed} &= p_1 p_2 d(\cos\theta), \end{aligned}$$

one finds

$$dN = \text{const}\, \frac{E_1 dE_1 E_2 dE_2 E_3 dE_3}{E_1 E_2 E_3} = \text{const}\, dE_1 dE_2 dE_3$$

The density of final states is obtained by dividing by dE_f, where $E_f = E_1 + E_2 + E_3$ is the total energy and, for E_1 and E_2 fixed, $dE_f = dE_3$. Thus

$$\rho = \frac{dN}{dE_f} = \text{const}\, dE_1 dE_2 \tag{E.8}$$

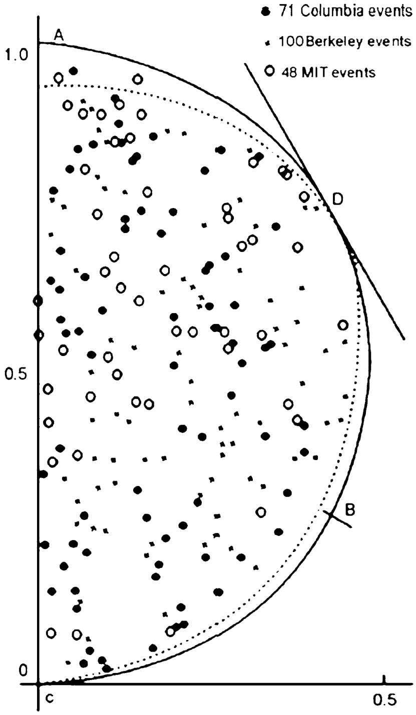


Fig. E.5 Observed distribution of events in $K \rightarrow 3\pi$, showing uniform population and thus $J_K = 0$. All events are plotted in one semicircle. The *dashed curve* is the boundary using relativistic kinematics and departs slightly from a circle [2]

when the matrix element M for the interaction is included.

$$\rho = \left|M(E_1, E_2)\right|^2 dE_1 dE_2 \tag{E.9}$$

Thus if one plots the events using E_1 and E_2 as coordinates, a diagram (Dalitz plot) is obtained in witch the accessible region in contained in a closed curve and the points representing the events are uniformly distributed within the curve if the matrix element in constant. Any departure from uniformity is to be attributed to the dependence of the matrix element on the momenta of the pions. Figure E.5 shows the observed distribution of events in $K \rightarrow 3\pi$, showing uniform population.

The three pion system may be treated in terms of a dipion, which here consists of two pions of like charge, plus an added third pion. Let the relative orbital angular momentum in the di-pion be l, and that of the third pion relative to the di-pion be L (see Fig. E.6) the parity of the three-pion system is then

$$(-1)^3(-1)^l(-1)^L = -(-1)^L$$

since the dipion must have even l for reasons of Bose symmetry. If $l > 0$ (i.e. $2, 4, \ldots$) the matrix element and Dalitz-plot density should vanish in the region C in Fig. E.1. If $L > 0$ (i.e. $1, 2, 3, \ldots$), the plot should be depleted in the region D, where the negative pion has very small energy relative to the dipion. Since the actual plot (Fig. E.5) is uniform throughout the expected circle neither l nor L can he non-zero hence it is concluded that $J_K = 0$.

Fig. E.6 Three pion system

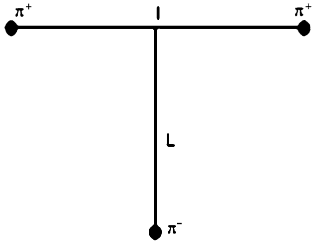
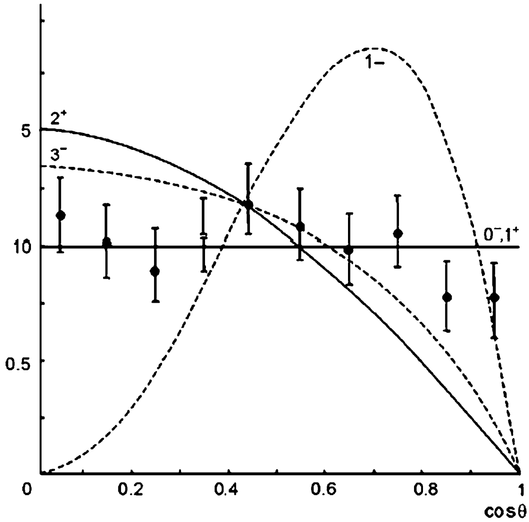


Fig. E.7 Distribution of $\cos\theta$ for the three-pion decay of k-meson



It must be stressed that the information on parity of K-meson cannot be extracted from the above analysis as parity is not conserved in weak decays and nothing can be said about the initial state. The Kaon parity may be determined by the study of hyper-nuclei (see AAK2,4).

The calculated distribution of $\cos\theta$ for the three-pion decay of K-meson is shown in Fig. E.7 for various spin-parity assignments. The approximately isotropic distribution agrees only with $J^{\pi} = 0^{-}$ or 1^{+} [3].

E.1.2 Dalitz Plots Involving Three Dissimilar Particles

When the decay products have different masses there is no virtue in using the triangular plot. One uses other plots that give similar information (see Sect. 5.1.1, AAK2) for the Dalitz plot for the detection of $\Sigma(1385)$ resonance in the $K^{-}p$ interactions as in Fig. 5.3, AAK2. Here we shall consider another example for the reaction

$$K^{+} + p \rightarrow K^{0} + p + \pi^{+}$$

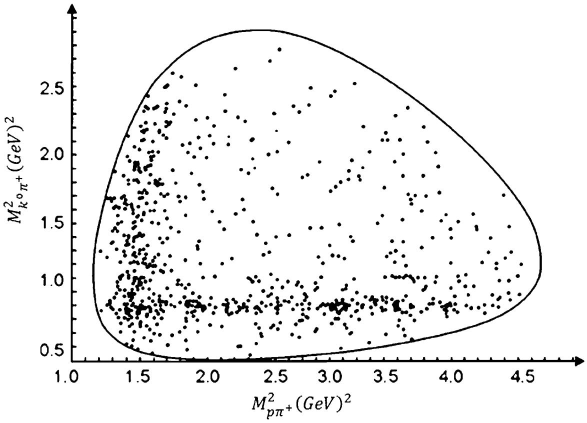


Fig. E.8 A Dalitz plot for the $K^+p \Rightarrow K^0 p\pi^+$ events. $pK^+ = 3.0$ GeV/c, 747 events [4]

For each event the invariant mass of the π^+–p system and the K^0–π^+ system is plotted one against the other we obtain the points as in Fig. E.8. In the absence of resonant systems the points would have been uniformly distributed throughout the indicated region. Actually two preferred energies for the two systems, one around 1235 MeV (corresponding to Δ^{++} resonance) and the other corresponding to K^{*+} resonance at 892 MeV are observed.

References

1. Dalitz (1953)
2. Orear et al. (1956)
3. Baldo-Ceolin et al., Nuovo Cimento **6**, 84 (1957)
4. M. Ferrro Luzzi et al., Nuovo Cimento **36**, 1101 (1965)

Appendix F

F.1 Properties of Selected Particles and Resonances

F.1.1 Gauge Bosons ($J = 1$)

Particle	Mass (MeV/c^2)	Width (GeV)	Decay modes and branching fractions
γ	$<3 \times 10^{-33}$	stable	–
W	$(80.49 \pm 0.67) \times 10^3$	<6.5	$e\nu_e$, 10 %; $\mu\nu_\mu$, 12 %; $\tau\nu_\tau$, 10 %
Z	$(91.49 \pm 1.39) \times 10^3$	<5.6	e^+e^-, 4.6 %

F.1.2 Leptons ($j = \frac{1}{2}$)

Particle	Mass (MeV/c^2)	Mean life (s)	Decay modes and branching fractions
ν_e	$<1.7 \times 10^{-5}$	stable	–
e^-	$0.51099906 \pm 0.00000016$	$>2 \times 10^{22}$ years	–
ν_μ	<0.25	stable	–
μ^-	105.65839 ± 0.00006	$(2.19703 \pm 0.00004) \times 10^{-6}$	$e^-\tilde{\nu}_e\nu_\mu$, 100%
ν_τ	<35	–	–
τ^-	1784.2 ± 3.2	$(3.3 \pm 0.4) \times 10^{-3}$	$\mu^-\tilde{\nu}\nu_\tau$, (17.8 ± 0.4) % $e^-\tilde{\nu}\nu_\tau$, (17.5 ± 0.4) % $\pi^-\nu_\tau$, (10.8 ± 0.6) % $\rho^-\nu_\tau$, (22.3 ± 1.1) %

A. Kamal, *Particle Physics*, Graduate Texts in Physics,
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F.1.3 Baryons ($J^P = \frac{1}{2}^+$)

Particle	I	S	Mass (MeV/c^2)	Mean life (s)	Decay modes and branching fractions
P	$\frac{1}{2}$	0	938.28	stable	–
n		0	939.57	899.7 ± 8.9	$pe^- \nu_e$, 100 %
Λ	0	−1	1115.60	2.631×10^{-10}	$p\pi^-$, 64.2 %; $n\pi^0$, 35.8 %; $pe^- \tilde{\nu}_e$, 8.3×10^{-4}
Σ^+	1	−1	1189.37	0.800×10^{-10}	$p\pi^0$, 51.64 %; $n\pi^+$; 48.36 %; $\Lambda e^+ \nu_e$, 2×10^{-5}
Σ^0		−1	1192.46	7.4×10^{-20}	$\Lambda\gamma$, ~100 %
Σ^-		−1	1197.34	1.479×10^{-10}	$n\pi^-$, ~100 %; $ne^- \tilde{\nu}_e$, 1.02×10^{-3}; $\Lambda e^- \tilde{\nu}_e$, 5.73×10^{-5}
Ξ^0	$\frac{1}{2}$	−2	1314.9	2.90×10^{-10}	$\Lambda\pi^0$, ~100 %
Ξ^-		−2	1321.32	1.64×10^{-10}	$\Lambda\pi$, ~100 %; $\Lambda e^- \tilde{\nu}_e$, 5.5×10^{-4}
Charmed baryon Λ_c^+	0	0	2284.9	1.8×10^{-13}	$pK^-\pi^+$, 2.2 %; and others

F.1.4 Baryon Resonances ($J^P = \frac{3}{2}^+$)

Particle	I	S	Mass (MeV/c^2)	Width (MeV)	Decay modes and branching fractions
$\Delta(1232)$	3/2	0	1232.0	115	(N)π, 99.4 %; (N)γ, 0.6 %
$\Sigma^+(1385)$	1	−1	1382.8	36	$\Lambda\pi$, 88 %; $\Sigma\pi$, 12 %
$\Sigma^0(1385)$		−1	1383.7	36	
$\Sigma^-(1385)$		−1	1387.2	39	
$\Xi^0(1530)$	1/2	−2	1531.8	9.1	$\Xi\pi$, 100 %
$\Xi^-(1530)$		−2	1535.0	9.9	
Ω^-	0	−3	1672.4	0.822×10^{-10} sec (lifetime)	ΛK^-, 67.8 %; $\Xi^0\pi^-$, 23.6 %; $\Xi^-\pi^0$, 8.6 %; $\Xi^0 e^- \tilde{\nu}_e$, 5.6×10^{-3}

F.1.5 Mesons ($J^P = 0^-$)

Particle	I	S	Mass (MeV/c^2)	Mean life or width	Decay modes and branching fractions
π^+	1	0	139.57	2.60×10^{-8} sec	$\mu^+ \nu_\mu$, ~100 %; $e^+ \nu_e$, 1.23×10^{-4}
π^0		0	134.97	0.84×10^{-16} sec	$\gamma\gamma$, 98.8 %

π^-		0	139.57	2.60×10^{-8} sec	$\mu^- \tilde{\nu}_\mu$, ~100 %; $e^- \tilde{\nu}_e$, 1.23×10^{-4}
η^0	0	0	548.88	1.08 keV 1.237×10^{-8} sec	$\pi^+\pi^0\pi^-$, 23.7 %; $3\pi^0$, 31.90 %; $\gamma\gamma$, 38.9 %
K^+	1/2	+1	493.65	K_s^0 0.8928×10^{-10} sec	$\mu^+\nu_\mu$, 63.5 %; $\pi^+\pi^0$, 21.2 %; $\pi^+\pi^-\pi^-$, 5.6 %; $\pi^0 e^+ \nu_e$, 4.8 %
K^0		+1	497.67	K_L^0 5.183×10^{-8} sec	$\pi^+\pi^-$, 68.6 %; $\pi^0\pi^0$, 31.4 %; $\pi^0\pi^0\pi^0$, 21.7 %; $\pi^+\pi^0\pi^-$, 12.4 %; $\pi^\pm\mu^\mp\nu_\mu$, 27.1 %; $\pi^\pm e^\mp \nu_e$, 38.7 %
$\eta'(958)$	0	0	957.57	0.24 MeV	$\eta\pi\pi$, 65.2 %; $\rho^0\gamma$, 30.0 %
$\eta_c(2980)$	0	0	2979.6	10.3 MeV	$\eta'\pi\pi$, 4.1 %; $K\tilde{K}\pi$, 5.5 %
D^+	1/2	0	1869.3	10.7×10^{-13} sec	e^+ any, 19.2 %; $K^-\pi^+\pi^+$, 7.8 %; $K^-\pi^+\pi^+\pi^0$, 3.7 %; $\tilde{K}^0\pi^+\pi^0$, 8.3 %; $\tilde{K}^0\pi^+\pi^+\pi^-$, 7.0 %
D^0		0	1864.5	4.3×10^{-13} sec	$e+$ any, 8 %; K^- any, 43 %; $K^-\pi^+\pi^0$, 12.5 %; $K^-\pi^+\pi^+\pi^-$, 7.9 %; $K^0\pi^+\pi^-$, 5.6 %
D_s^+	0	−1	1969.3	4.4×10^{-13} sec	$\phi\pi^+$; $\phi\pi^+\pi^+\pi^-$
Bottom mesons					
B^+	1/2	0	5277.6	1.4×10^{-12} sec	$\tilde{D}^0\pi^+$, 0.5 %; $D^{*-}(2010)\pi^+\pi^+\pi^0$, 4.3 %
B^0		0	5275.2		ψ any, 1 %; $\tilde{D}^0\pi^+\pi^-$, <3.9 %; $D^{*-}(2010)\pi^+$, 0.3 %

F.1.6 Mesons ($J^P = 1^-$)

Particle	I	S	Mass (MeV/c^2)	Width (MeV)	Decay modes and branching fractions
$\rho(770)$	1	0	770.0	153.0	$\pi\pi$, ~100 %; e^+e^-, 0.0044 %
$\omega(783)$	0	0	782.0	8.5	$\pi^+\pi^-\pi^-$, 89.3 %; $\pi^0\gamma$, 8.0 %; e^+e^-, 0.0071 %
$\phi(1020)$	0	0	1019.4	4.41	K^+K^-, 49.5 %; K_s^0 and K_L^0, 34.4 %; $\pi^+\pi^-\pi^0$, 1.9 %; e^+e^-, 0.031 %
$K^{*+}(892)$	1/2	+1	892.1	51.3	$K\pi$, ~100 %
$K^{*0}(892)$		+1			
$J/\psi(3097)$	0	0	3096.9	0.068	e^+e^-, 6.9 %; hadrons + radiative, 86.2 %; $\mu^+\mu^-$, 6.9 %
$\gamma(9460)$	0	0	9460.3	0.052	e^+e^-, 2.5 %; $\tau^+\tau^-$, 3.0 %; $\mu^+\mu^-$, 2.6 %
$D^{*+}(2010)$	1/2	0	2010.1	<2.0	$D^0\pi^+$, 49 %; $D^+\pi^0$, 34 %
$D^{*0}(2010)$		0	2007.1	<5	$D^0\pi^0$, 52 %; $D^0\gamma$, 48 %

Appendix G

G.1 Introductory Astrophysics

Particle astrophysics or Astro particle physics is a new branch of particle physics that studies elementary particles of astronomical origin, and their relation to astrophysics and cosmology.

The basic questions particle astrophysics attempts to answer are:

- Does the proton decay?
- What is the role of neutrinos in cosmic revolution?
- What is the origin of cosmic rays?
- What is the nature of gravitation?
- Can we detect gravitational waves?
- What is the ultimate faith of a black hole?
- What is the nature of dark matter?

The most active topics in astro particle physics being pursued are:

- Gamma-ray astronomy
- Neutrinos and neutrino astronomy
- Magnetic monopoles
- Axions

Interaction	Relative strength	Exchange particle
Strong	1	Given, spin 1, $m = 0$, quarks and binding nuclei
Electromagnetic	10^{-2}	photon between charged particles, spin 1 zero mass
Weak	10^{-7}	Weak bosons, $W^{\pm}$, Z^0, spin 1, $m_w = 80$ GeV and $m_{z^0} = 91$ GeV

For W and Z bosons, effective range of interaction $r_0 = \hbar/M_c \approx 0.0025$ fm. Photon carries two types of charges $+$ and $-$.

A. Kamal, *Particle Physics*, Graduate Texts in Physics,
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Coupling of photon is

$$e^2 = 4\pi\alpha\hbar c$$

where e is the electric charge, $\hbar = c = 1$ and $\alpha = 1/137$.

Strong Colour Interactions Coupling of the quark to gluon → $P_s^2 = 4\pi\alpha_s$, $\alpha_s \approx 1$.

Number of strong charges $= 6$ (R, B, G, $+3$ anti colour)

Photon does not carry charge but gluon does, one colour and one anti colour.

Weak Interactions

$$W^{\pm},\ Z^0$$

$W^{\pm}$ is called the *charged current weak interaction* and Z^0 is the *neutral current weak interaction.*

Electroweak Interaction Two aspects of the electromagnetic and weak interactions.

$$\begin{aligned} &M_{WZ} \sim \frac{e}{\sqrt{G_F}} = \sqrt{\frac{4\pi\alpha}{G_F}} \sim 100\ \text{GeV} \\ &G_F = 1.17 \times 10^{-5}\ \text{GeV}^{-2} \end{aligned}$$

Electroweak means → couplings of W^- and Z bosons to the fermions is same as that of photon. $g_W = e$.

Gravitational Interactions Dimensionless

$$\frac{GM^2}{4\pi\hbar c} = 5.3 \times 10^{-40}$$
$$\left(Mc^2 = 1\ \text{GeV}\right)$$

Compare with

$$\frac{e^2}{4\pi\hbar c} = \frac{1}{137.036}$$

The Quark-Gluon Plasma (QGP) Quarks are not to be found as free particle but as three quark and antiquarks bond states, called hadrons. The quark confinement is a low energy phase but at sufficiently high temperature and density, quarks and gluons are expected to undergo a phase transition and transform into a plasma analogous to the plasma of positive ions and electrons at high temperatures when electrons and positive ions form a plasma. If such a QGP is reproduced at high level density and temperature, the state of affairs in the very early stages (the first 25 µsec) of the big bang would have been realized before the temperature fell as the expansion took place and QGP froze into hadrons.

To this end heavy ion colliders mainly at the RHIC heavy ion collider at the Brookhaven national laboratory, and the large Hadron collider at CERN, have operated (1980–1990) by smashing relativistic lead ions against each other, gold-ions against each other. The critical quantity is the energy density of the nuclear matter during the very brief (10^{-23} sec) period of the collision. In lead-lead collisions at 0.16 GeV per nucleon in each of the colliding beams, a threefold enhancement has been observed in the frequency of strange particles and antiparticles (from creation of $s\bar{s}$ pairs) as compared with proton-lead collisions at a similar energy per nucleon.

Although the results have yet to be independently verified as of February 2010, claims have been made for the creation of QGP at approximate temperature of 4 trillion degrees Celsius.

New Particles Standard Model of particle physics explains accurately in detail all experiments, at accelerators and reactors, but does not describe building blocks on large scales (~5 % of energy density only explained). Study of large scale cosmic structures, galaxies, galaxies clusters and superstructures, bulk of matter in universe is invisible (non-luminous) dark matter.

Nature and origin of dark matter so far unknown, possible candidates like fermions and bosons could be super symmetric particles. So far there is no direct experimental evidence for individual dark matter.

Dark energy exceeds any other form, following Big Bang expansion had slowed down because of pull of gravity, but now accelerating because of repulsion of dark energy.

There is no experimental evidence for grand unification of electro-weak with gravitation.

Quarks confinement is expected to disappear at high temperature ($kT > 0.3$ GeV) and hadrons would undergo phase transition to a quark-gluon plasma.

Hubble Expansion Milky way contains $\sim 10^{11}$ stars.

Among the various types of galaxies observed, the most common are elliptical and spiral. Milkyway is an elliptical one.

Negative gravitational energy GM^2/R and the mass energy Mc^2 of the universe are about equal being $\cong 10^{70}$ J, so that total energy is zero.

In 1929, Hubble used a 100 inch Mount Wilson telescope to observe the Red shift of the spectral lines from various galaxies, due to Doppler effect. Shift depending on the apparent brightness of galaxy and hence on distance.

He also measured the recession velocity v, of a galaxy.

$$\lambda' = \lambda\sqrt{\frac{1+\beta}{1-\beta}} = \lambda(1+z)$$

where $\beta = \frac{v}{c}$ and red shift $z = \Delta\lambda/\lambda$.

Linear relationship between v and distance r.

$$v = H_0 r$$

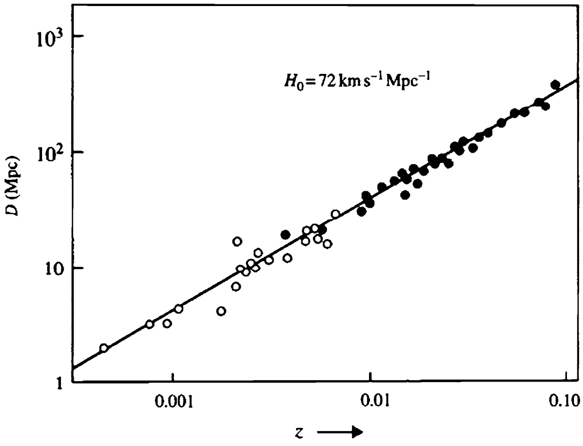

Fig. G.1 Log-log plot of distance versus red shift

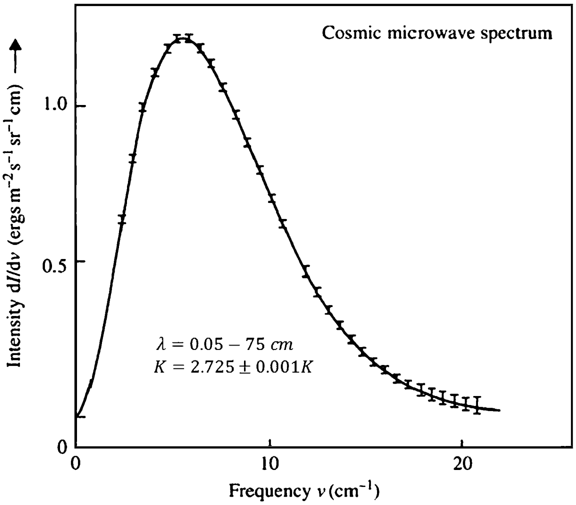

Fig. G.2 Cosmic microwave spectrum

H = Hubble constant. $H_0 = 70 \pm 10$ km s^{-1} Mpc^{-1}. 1 Mpc = Mega parsec = 3.09×10^{19} km.

If expansion is accelerating or decelerating H will be a function of time.

Subscript 0 to $H \rightarrow$ value measured today.

Interpretation of red shift applicable only for small red shifts $z < 0.003$, for nearby galaxies ($z = v/c$). Empirical relation has linear dependence of the red-shift on the distance of galaxy, as shown in Fig. G.1. Distance is estimated from apparent brightness or luminosity.

Cosmic Microwave Radiation Spectrum Cosmic microwave radiation was discovered when scientists were searching for sources of radio waves and landed with a background of microwaves that were isotropic. Figure G.2 shows the spectral dis-

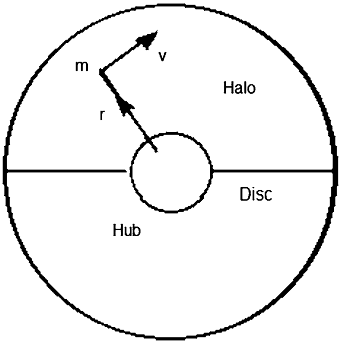

Fig. G.3 An end-on view of a spiral galaxy, consisting of a central hub, a disc, and a possible halo of dark matter

tribution of radiation as recorded by the COBE satellite and compared with Max Planck's black body radiation distribution.

The origins of cosmic microwave radiation traces back to Big Bang, when a photon fireball was cooled by expansion to a few degrees K. This showcases that in early history, universe radiation dominated and now it is matter dominated.

Note: For unification the three running constants are not meeting at the same point.

Dark Matter Indirect evidence: Missing mass from spiral galaxies (non-luminous matter).

A spiral galaxy such as our own has most of luminous material concentrated in central hub + thin disc, shown in Fig. G.3.

Let m be the mass at a distance r from galactic centre moving with tangential velocity v.

Equating gravitational and centrifugal forces

$$\frac{mv^2}{r} = \frac{mM(< r)G}{r^2}$$

where $M(< r)$ is the mass inside r.

For a star inside hub,

$$M < r \propto r^3$$
$$\therefore \quad V \propto r$$

For outside hub, $M \sim$ constant

$$\therefore \quad V \propto r^{-1/2}$$

Therefore, velocity should increase at small r and decrease at large r. However for many spiral galaxies the rotation curves are quite flat at large r values, leading to suggestion bulk of galactic mass (80–90 %) is in form of dark matter in a halo.

Also, the mismatch between the motional energy and gravitational energy requires presence of dark matter.

Effects of galaxy clusters can also be estimated directly by their effects on the images of more distant quasars.

Further dark matter is also required to account for the level of fluctuations of cosmic ray microwave background.

Baryonic Dark Matter Baryonic matter makes only a small contribution to overall contribution of the universe and a less than 25 % to the estimated total density of dark matter.

Neutrinos The favoured hypothesis is that non-baryonic dark matter is made up of elementary particles, created at an early hot stage of the universe and stable enough to have survived to the present day.

$$\gamma \leftrightarrow e^+ + e^- \leftrightarrow \nu_i + \overline{\nu}_i$$

where $i = e, \mu, \tau$.

The total energy density would be equal to the critical density if the sum of the masses of three flavours has the value

$$\sum_{e,\mu,\tau} m_\nu c^2 = 47\ \text{eV} \tag{G.1}$$

Thus relic neutrinos with mass range could make significant contribution to dark matter.

However, evidence from neutrino oscillations suggests very much smaller masses then indicated by C.

Axions The axion is a very light pseudoscalar particle (spin-parity 0^-) postulated in connection with the absence of CP violation in strong interactions quantum chromodynamics (QCD), and these would be T-violating or CP violating, as they are the weak interactions. There is no laboratory evidence for such a particle but it is a possible candidate for dark matter. The characteristics of axions—the mass m_a and the vanishingly small coupling—depend on just one parameter, which is the unknown scale of the symmetry-breaking interaction.

WIMPS The most popular hypothesis, currently, for dark matter particles (WIMPs), moving with non-relativistic velocities at the time of freeze-out and thus constituting cold dark matter.

For several reasons it is considered that super symmetric particles could be the most likely WIMP candidates. So far, there is no laboratory experiment to prove their existence.

Cosmic Rays Cosmic rays actually consist of high energy particles incident on the earth from outer space plus the secondary particles which they produce as they traverse the atmosphere.

Composition

Charged Primary Particles Protons (86 %), α-particles (11 %), nuclei of heavier elements up to uranium (1 %), and electrons (2 %).

Neutral Particles γ-rays, neutrinos and antineutrinos. Some of them can be identified as coming from point sources as γ-rays from crab nebula and active galactic nuclei, neutrinos from the sun and from supernovae.

Chemical Composition It bears a remarkable resemblance to the solar system abundances, except the big differences in those of Li, Be and B. Their comparative abundance in cosmic rays is due to spallation of carbon and oxygen nuclei as they traverse the interstellar hydrogen.

The Energy Density This is about 1 eV cm$^-$1 in deep space outside the influence of solar system magnetic fields, comparable with energy density in star light of 0.6 eV cm^{-3}, or cosmic microwave background radiation of 0.26 eV, or galactic magnetic of 0.25 eV cm^{-3}.

Energy Spectrum The energy spectrum of cosmic rays, above a few GeV, upto the so-called "knee" at 10^{14} eV (100 TeV) follows a simple power law

$$N(E)dE = \text{const}\, E^{-2.7} dE \tag{G.2}$$

Above the "knee" the spectrum becomes steeper with an index of about -3.0 before apparently off again above 10^{18} eV.

Acceleration of Cosmic Rays Many years ago the mechanism for the acceleration of cosmic rays to such colossal energies as 10^{20} eV and the form of energy spectrum were considered. The shock-wave acceleration from supernovae shells appears capable of accounting for the energies of cosmic ray nuclei of charge $Z|e|$ upto about 100Z TeV (10^{14} ZeV), but not beyond. There are many possible sources of shocks, but Type II supernovae shells seem to be good candidates, with shock velocities of order 10^7 m s^{-1}. A Type II supernova typically ejects a shell of material of about $10M_0$ (2×10^{31} kg), with velocity of order 10^7 m s^{-1} into the inter stellar medium approximately once per century in our galaxy. Acceleration could occur due to shock fronts. A relativistic particle travelling in the positive x-direction, which traverses a shock-front $-u_1$ in the negative x-direction. Suppose that the particle is backscattered by the field in the ionized gas behind the front. Thus, the particle travels back across the shock-front, to be scattered by magnetized cloud, upstream of the front. If these scatter the particle backwards again (i.e. in the direction of positive x) the particle can re-cross the front and repeat the cycle of acceleration once more. Application of the Lorentz transformations shows that the fractional energy gain is of the order of the shock-front velocity.

Geomagnetic Effects East-West effect, i.e.; that at all latitudes, more (positively charged particles) arrive from the west than from the east, because of the lower momentum cut-off. The effect arises because all positively charged particles are deflected in a clockwise spiral, as viewed from above the N-pole. The detailed theory is originally due to Stormer. In particular in NW Europe, with $\lambda \sim 50°$N the vertical cut-off momentum would be 1.1 GeV c^{-1}. At the magnetic equator the vertical cut-off is 14.9 GeV c^{-1}, from the eastern horizon it is 59.6 GeV c^{-1} while that for particles from the western horizon it is only 10.2 GeV c^{-1}.

Secondary Cosmic Radiation Nuclear interaction mean free path (MFP) is $\sim$100 gm cm^{-2} for a proton compared with a total atmospheric depth of $X =$ 1030 gm cm^{-2}, the pions will be created mostly in the stratosphere Nuclear absorption will only become important for energies of order 100 GeV or more and at energies practically all charged pions decay in flight rather than interact.

At high (TeV) energies, on the contrary, majority of the pions undergo nuclear interaction before they have a chance to decay.

Muons produced from the decay of charged pions will decay in the flight ($E_\mu \leq$ 1 GeV). However, muons of energy 3 GeV has $\sim$20 km decay length and even with ionization energy loss of 2 MeV gm^{-1} cm^2 of air traversed are able to reach the sea level and go underground. Muons are said to be the **hard components** of cosmic radiation.

Neutral pions undergo electromagnetic decay $\pi^0 \to 2\gamma$ with an extremely short lifetime of 8×10^{-17} sec. This develops electron-photon cascades mostly in the high atmosphere. The cascade is easily absorbed. This constitutes the soft component of cosmic rays.

Quasars (Quasi-Stellar Radio Sources) Brightest optical and radio sources in the sky, far exceeding total light output from their host galaxies. Quasars invariably have large red shifts (upto $z \approx 5$) and correspond to most distant events in the development of the universe—billion of years ago when galaxies were formed.

Quasars are believed to be associated with very massive black holes of typically 10^6–$10^8 M_\odot$.

Pulsars Although the early theory of neutron stars was developed shortly after Chadwick discovered the neutron in 1932, major experiments had to wait the discovery of Pulsars by Hewish et al. [1]. Pulsars are rapidly rotating neutron stars which emit radiation at short and extremely regular intervals much like a rotating lighthouse beam which crosses the line of sight of an observer with regular frequency. Over 1000 pulsars are known with rotational periods ranging from 1.5 ms to 8.5 s. Only about 1 % of pulsars can be associated with past supernova remnant, since over millions of years the neutron stars have drifted from the remnant nebula. For a few young pulsars like that in the Crab the nebula is still associated with most famous example of a pulsar which has a period of 33 ms, and is remnant of the AD 1054 supernova recorded by the Chinese. Besides the radio pulsars, some 200 X-ray pulsars are known.

Stellar Stability At high densities as in stellar cores at an advanced stage, a new form of pressure called electronic degeneracy pressure becomes important apart from gas pressure and radiative pressure. At absolute zero temperature the gas falls into quantum states of the lowest possible energy and the gas is said to be degenerate. Because of Pauli's principle each quantum state can be occupied by one electron only. If the degeneracy pressure wins over the inward gravitational pressure to prevent contraction then the maximum mass of a stellar core which is stable against collapse is given by

$$M_{ch} = 1.4 M_{\odot} \tag{G.3}$$

The quantity M_{ch} is called the Chandrasekhar mass after the physicist who first discussed the stability of white dwarfs and obtained the above limit in 1931.

White Dwarf Stars Stars of relatively low mass such as our own after passing through the hydrogen- and helium-burning phases will form cores of carbon and oxygen. Higher temperature of the core enables helium to be burned in a spherical shell surrounding the core and the stellar envelope will expand by a huge amount and eventually escape to form a planetary nebula surrounding the star. The star providing its mass is less than the Chandrasekhar mass and is saved from a catastrophic collapse because of the electron degeneracy pressure in the core. Such a star bereft of its envelope and slowly cooling off is known as a **white dwarf**. All main sequence stars (sun, Sirius and alpha Centauri A and B are all main sequence stars) will end up eventually as white dwarfs. However these stars are limited to a fairly narrow mass range. The upper limit is determined by $M_{ch} = 1.4 M_{\odot}$ but there is also a lower limit of $0.25 M_{\odot}$.

The typical radius of a white dwarf is of the order of 1 % of the solar radius corresponding to the fact that, the average density is of the order of 10^6 times the mean solar density. For a white dwarf of about one solar mass the central density is calculated $\approx 10^{11}\ \mathrm{kg\,m^{-3}}$. Since white dwarfs as the name implies emits white light they have surface temperatures of the same order as that of the sun so that with almost 100 times smaller radius their luminosities are of the order of 10^{-3} of the solar luminosity. This guarantees that even with no nuclear energy source white dwarfs can continue shining for billions of years.

Neutron Stars Neutron star is a type of stellar remnant that can result from the gravitational collapse of a massive star during a super-novae event. The rump left behind after a supernova explosion is a neutron star, which contains neutrons, protons, electrons and heavier but with neutrons predominating.

Neutrons play a similar role in supporting a neutron star as degenerate electrons do in supporting a white dwarf. The limit to which the degenerate neutron gas can do this is analogous to the Chandrasekhar limit for electron-electron degeneracy in white dwarfs.

The limit now becomes

$$M_{max} \approx 5 M_{\odot} \tag{G.4}$$

The fate of a neutron star that undergoes gravitational collapse is a black hole.

Let R_{schw} be the Schwarzschild radius associated with a black hole for an object of mass M given by the formula

$$R_{schw} = \frac{2GM}{c^2} \tag{G.5}$$

As an example let R_{schw} radius of a star of mass $M = 5M_{\odot}$ is 10 km. Equation (G.5) implies that when the physical radius of a collapsed star falls inside R_{schw} there are no light paths to outside world. Photons from the star cannot escape its gravitational field and it becomes black to an outside observer. However an observer with R_{schw} radius would record lots of activity but would not be able to communicate with the outside world.

Black holes are inevitable consequences of Einstein's general theory of relativity.

Hawking Radiation from Black Holes In 1974 Hawking proved that in very strong gravitational field the black holes are able to emit (thermal) radiation.

Hawking temperature for a black hole of mass M is given by

$$kT_H = \frac{\hbar c^3}{8\pi GM}$$

Thus, for $M = 5M_{\odot}$, $T_H \approx 8 \times 10^{-8}$ K.

Note that as the black hole loses energy and mass, it gets hotter and thus a black hole will eventually evaporate and disappear.

The lifetime is given by

$$\tau_{BH} = \text{const} \times \frac{G^2M^3}{\hbar c^4} \approx 10^{66} \left(\frac{M}{M_0}\right)^3 \text{ yr.}$$

Thus the time for a black hole of a typical astronomical mass to evaporate is far longer than the age of the universe.

Neutrinos from SN1987A SN1987A was a supernova in the large Magellanic cloud some 60 kpc from the Milkyway. The light from the supernova reached the earth on February 23, 1987. As it was the first supernova discovered in 1987, it was labeled "1987A". It occurred approximately 51.4 kilo parsecs from Earth, approximately 170000 light years, close enough that it could be seen from the naked eye from the southern hemisphere. It is the famous supernova from which interactions of the emitted neutrinos were observed simultaneously in the Kamiokande and IMB water Cerenkov detectors, originally designed to detect proton decay. The neutrino pulse was actually detected about seven hours before the optical signal became detectable.

The important reactions that could lead to detection of supernova neutrinos in a water detector are as follows

$$\overline{\nu_e} + p \rightarrow n + e^+ \tag{G.6}$$

$$\nu + e^- \rightarrow \nu + e^- \tag{G.7}$$

$$\overline{\nu} + e^- \rightarrow \overline{\nu} + e^- \tag{G.8}$$

The first supernova recorded by Chinese and Muslim astronomers in 185 A.D.

The integrated neutrino luminosity calculated from the event rates was

$$L \approx 3 \times 10^{46} \text{ J} \approx 2 \times 10^{59} \text{ MeV} \tag{G.9}$$

with an uncertainty of a factor of two.

Equation (G.9) is in excellent agreement with the calculated gravitational energy by 1.8×10^{59}. Altogether approximately 10^{58} neutrinos were emitted and even at the earth, some 170000 light years distant the flux survived a journey without attenuation implies their stability since the neutrino pulse looked less than 10 sec, the transit time of neutrinos of different energies was the same within one part in 5×10^{11}. The time of arrival on Earth, t_E will be given in terms of the emission time from the supernova, t_{SN}, its distance and the neutrino mass m and energy E by

$$t_E = t_{SN} + \left(\frac{L}{C}\right)\left[1 + \frac{m^2c^4}{2E^2}\right]$$

for $m^2 \ll E^2$. For two events with different energies E_1 and E_2 the time difference will be given by

$$\Delta t = |\Delta t_E - \Delta t_{SN}| = \left(\frac{Lm^2c^4}{2c}\right)\left[\frac{1}{E_1^2} - \frac{1}{E_2^2}\right] \tag{G.10}$$

For typical values $E_1 = 10$ MeV, $E_2 = 20$ MeV and $\Delta t < 10$ sec, (G.10) gives $m < 20$ eV, a poorer limit than obtained from tritium beta decay.

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Appendix H

Landmarks in chronological order for the development of Nuclear Physics (♣), Particle Physics (♡), Particle Astrophysics (♦), award not given in physics (♠), award given in physics not connected with ♣, ♡, ♦, (†) are indicated by corresponding abridged Nobel Prize citations.

♣ 1901: W.C. Rontgen—citation “for discovery of X-rays”

† 1902:

♡ 1903: A.H. Becquerel, Pierre Curie and Marie Curie—citation “for spontaneous radioactivity”

† 1904:

♣ 1905: P.E.A. Lenard—citation “for work on Cathode rays”
♣ 1906: Sir J.J. Thompson—citation “for Conduction of electricity through gases”
♦ 1907: A.A. Michelson—citation “for precision interferometer especially for the negative result for the existence of ether”

† 1908:
† 1909:
† 1910:
† 1911:
† 1912:
† 1913:

♣ 1914: M.V. Laue—citation “for discovery of the diffraction of X-rays by crystals”
♣ 1915: Sir W.H. Bragg and Sir W.L. Bragg—citation “for analysis of crystal structure by means of X-rays”

♠ 1916:

♣ 1917: C.G. Barkla—citation “for discovery of the characteristic Rontgen radiation of the elements”
♡ 1918: Max Planck—citation “for discovery of energy quanta”

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♣ 1919: Johannes Stark—citation "for discovery of Doppler Effect in canal rays and splitting of spectrum lines in electric fields"

† 1920:

♣ 1921: Albert Einstein—citation "for theoretical physics and especially for the law of photoelectric effect"
♣ 1922: Neil Bohr—citation "for structure of atoms and radiation emanating from them"
♣ 1923: R.A. Milikan—citation "for elementary charge of electricity and photoelectricity"
♣ 1924: K.M.G. Siegbahn—citation "for discoveries in X-ray spectroscopy"

† 1925:
† 1926:

♣ 1927: A.H. Compton—citation "for Compton effect" and C.T.R. Wilson—citation "for his method of making the paths of electricity visible by condensation of vapor"
♣ 1928: Sir Owen Williams Richardson—citation "for thermionic phenomenon"
♣ 1929: Prince L.V. De Broglie—citation "for his discovery of the wave nature of electrons"

† 1930:
♠ 1931:

♣ 1932: Werner Heisenberg—citation "for the creation of quantum mechanics"
♣ 1933: Erwin Schrodinger and P.A.M. Dirac—citation "for new productive forms of atomic theory"

♠ 1934:

♡ 1935: Sir James Chadwick—citation "for the discovery of neutrons"
♡ 1936: C.D. Anderson—citation "for the discovery of positron"
♦ V.F. Hess—citation "for discovery of cosmic radiation"
♣ 1937: C.J. Davisson and Sir G.B. Thompson—citation "for experimental discovery of diffraction of electrons by crystals"
♣ 1938: Enrico Fermi—citation "for existence of new radioactive elements produced by neutron irradiation and discovery of nuclear reactions by slow neutrons"
♡ 1939: E.O. Lawrence—citation "for cyclotron and results on artificial radioactive elements"

♠ 1940:
♠ 1941:
♠ 1942:

♣ 1943: Otto Stern—citation "for development of molecular ray method and discovery of magnetic moment of proton"
♣ 1944: Isaac Rabi—citation "for resonance method for recording magnetic properties of atomic nuclei"

♣ 1945: Wolfgang Pauli—citation “for discovery of exclusion principle (Pauli’s principle)”

† 1946:
† 1947:

♣ 1948: Lord P.M.S. Blackett—citation “for development of the Wilson cloud chamber method, and discoveries in nuclear physics and cosmic radiation”
♡ 1949: Hideki Yukawa—citation “for his prediction of the existence of mesons on the basis of theoretical work on nuclear forces”
♡ 1950: C.F. Powell—citation “for development of photographic method and discoveries regarding mesons with this method”
♣ 1951: Sir J.D. Cockcroft and E.T.S. Walton—citation “for transmutation of atomic nuclei by artificially accelerated atomic particles”
♣ 1952: Felix Bloch and E.M. Purcell—citation “for nuclear magnetic precision measurements (MRI)”

† 1953:

♡ 1954: Walter Bothe—citation “for coincidence method”
♣ 1955: W.E. Lamb—citation “for fine structure of hydrogen spectrum and Polykarp Kusch “for precise magnetic moment of electron”

† 1956:

♡ 1957: C.N. Yang and T.D. Lee—citation “for violation of parity in weak interactions (matter- anti matter asymmetry)”
♡ 1958: P.A. Cerenkov, I.M. Frank and I.Y. Tamm—citation “for discovery and interpretation of the Cerenkov effect”
♡ 1959: E.G. Segré and Owen Chamberlain—citation “for discovery of antiproton”
♡ 1960: D.A. Glaser—citation “for invention of bubble chamber”
♣ 1961: Robert Hofstader—citation “for scattering in atomic nuclei and structure of nuclei and R.L. Mösbauer “for recoilless absorption of gamma radiation”

† 1962:

♣ 1963: M.G. Mayer and J.H.D. Jenson—citation “for nuclear shell structure” and E.P. Wigner “for symmetry principles in particles and nuclei”

† 1964:

♡ 1965: S.I. Tomenaga, Julian Schwinger and R.P. Feynman—citation “for quantum electrodynamics related to elementary particles”

† 1966:

♦ 1967: H.A. Bethe—citation “for energy production in stars”
♡ 1968: L.W. Alvarez—citation “for discovery of a large number of resonance states, large hydrogen bubble chamber and data analysis”
♡ 1969: Murray Gell-Mann—citation “for classification of elementary particles and their interactions”

† 1970:
† 1971:
† 1972:
† 1973:

♦ 1974: Sir Martin Ryle—citation “for aperture synthesis technique and Antony Hewish for radio astrophysics (pulsars)”
♣ 1975: Aage Bohr, Ben Mottelson and James Rainwater—citation “for discovery between collective motion and particle motion in atomic nuclei”
♡ 1976: Burton Richter Samuel Ting—citation “for discovery of a heavy elementary particle of a new kind (ψ/J)”

♠ 1977:

♦ 1978: A.A. Penzias and R.W. Wilson—citation “for discovery of cosmic microwave background radiation”
♡ 1979: S.L. Glashow, Abdus Salam and Steven Weinberg—citation “for unified weak and electromagnetic interaction between elementary particles including prediction of weak neutral current”
♡ 1980: J.W. Cronin and V.L. Fitch—citation “for CP violation in neutral K-meson”

† 1981:
† 1982:

♦ 1983: S. Chandrasekhar—citation “for theoretical studies of structure and evolution of stars and W.A. Fowler “for theoretical and experimental studies of nuclear reactions leading to chemical elements in the universe”
♡ 1984: Carlo Rubbia and Simon Vander Meer—citation “for stochastic cooling which led to the discovery of W and Z bosons”

† 1985:
† 1986:
† 1987:

♡ 1988: L.M. Lederman, Melvin Schawartz and Jack Steinberger—citation “for neutrino beam method and discovery of muon neutrino”

† 1989:

♡ 1990: J.L. Friedman, H.W. Kendall and R.E. Taylor—citation “for deep inelastic scattering of electrons and bound neutrons—important for quark model”

† 1991:

♡ 1992: Georges Charpak—citation “for invention of multiwire proportional chamber”
♦ 1993: R. A. Hulse and J.H. Taylor Jr.—citation “for study of gravitation by pulsar”
♡ 1994: B.N. Bruckhouse and C.G. Shull—citation “for development of neutron scattering technique”

♡ 1995: M.L. Perl and Froderin Reines—citation "for lepton physics"

♡ 1999: G. Hooft and M.J.G. Veltman—citation "for quantum structure of electroweak interactions"

♡ 2004: D.J. Gross, H.D. Politzer and F. Wilczek—citation "for discovery of asymptotic freedom in the theory of strong interaction"

♡ 2008: Y.C. Nambu, Makoto Kabajashi and Toshide Masakawa—citation "for mechanism of spontaneous broken symmetry—quantum mechanical explanation of CKM matrix"

♦ 2011: Saul Perlmutter, B.P. Schimdle and A.G. Reiss—citation "for discovery of accelerating expansion of universe through observation of distant supernovae"

Some Interesting Facts

- Father and son combination: Neil Bohr and Aage Bohr, Sir W.L. Bragg, Sir W.L. Bragg.
- Youngest Nobel Laureate: (age 25) William Laurence Bragg.
- Only Laureate to win the Nobel prize twice in Physics: 1952 and 1956—John Bardeen.
- Marie Curie received Nobel prize twice in different subjects—physics in 1903 and chemistry in 1911.

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