KINEMATICS OF NEUTRAL HADRON IN AN ELECTRON-PROTON COLLIDER

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ABSTRACT

In the an electron-proton collider, neutral hadrons were produced in the hadronisation process that occurred just after the electron-proton collision. The neutral hadrons were produced at interaction point using reference energy from its centre-of-mass. In this paper, we discuss the kinematics of particles produced from its centre-of-mass and the hadronisation process follows after such collision.

ABSTRAK

Dalam pelanggaran electro-proton pada tenagan tinggi , hadron neutral dihasil dalam proses hadronisasi yang berlaku sejurus selepas perlanggaran electron-proton. Hadron neutral dihasilkan dari pusat-jisim pada titik interaksi. Dalam kertas kini, kinematik zarah yang terhasil dari pusat-jisim dan proses hadronisasi yang menghasil hadron neutral ini dibincangkan.

Keywords: neutral hadrons, kinematics, hadronisation

INTRODUCTION

In the an electron-proton collider, quarks are produced when the proton beam and proton moving at high speed in the range of hundreds of Giga electron Volts, collided in centre of its particle detector. During this collision, the quarks in proton (two ups and one down quarks) are also accelerated at high speed; with its kinematics describe using special theory of relativity. As a result from these collisions, free quarks were produced at the centre-of-mass in the detector, when the quarks within the proton structure interacted with virtual photon γ^* produced by the incoming electron experience de-acceleration during the collision. As the free quarks underwent hadronisation process that turn them into a bound state to form hadrons that are more stable. Hadronisation occurs when free quarks and antiquarks combine together through interaction with force carrier(s) such as photon, bosons or gluons.

HADRONIZATION

In Quark Parton Model (QPM), the virtual photon γ^* behave in a point-like manner, and the quarks *uud* in proton are assumed to be free and point like, called partons. Thus, the electron-proton collision is treated as an incoherent sum of a two body that consist of elastic electron – parton with the scattering cross section weighted by a parton density distribution function $f_i(x)$, given by Callan-Gross relations as [5],:

$$F_2(x) = x\sum_i e_i^2 f_i(x) \tag{1}$$

and,

$$F_1(x) = \frac{1}{2x} F_2(x) \tag{2}$$

with F_1 and F_2 as the structure functions, e_i as the charge of the parton, and $f_i(x)dx$ is the probability of finding a parton-*i* in the momentum interval of *x* and *x+dx.* **Figure 1** illustrates the QPM for electron-proton collision. The parton density distribution were generated by particle generators such as Phytia and Ariadne.

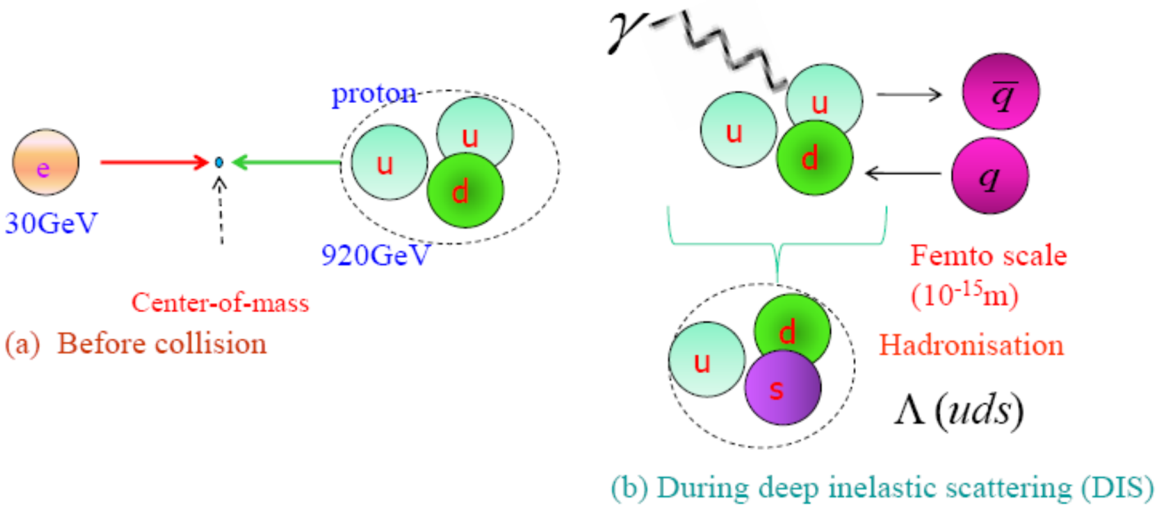

Figure 3(a) Quark parton Model (QPM) treats electron-proton collision as incoherent sum of a two point like partons;

(b) In deep inelastic scattering (DIS), hadronisation of quarks *uds* into Λ occurred. (Λ^0 decay through $\Lambda \to n\pi^0$ channel (35.8% yield), mean life $2.631\times10^{-10}\,s$)

In Lund String Model, the hadronisation of quarks and gluons to form hadrons involves the fragmentation of color flux sring-like gluons that are binding the quarks and antiquarks ($q\bar{q}$) into hadrons (**Figure 2**). The string of strong color field that binds the quark and antiquark may be stretched in the final state radiation, just before hadronisation took place during the electron-proton collision [4].

In the string-fragmentation scheme, the color field between the partons (i.e. quarks and gluons) may be fragmenting itself with the emission of energetic gluon carry "kinks" on the string. If the energy stored in the string is sufficient enough as when two color partons move apart, a $q\bar{q}$ pair may be created from the vacuum.

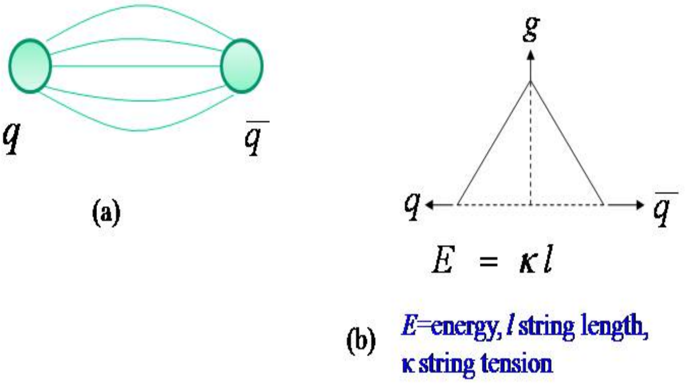

Figure 2. The Lund string model (a) q and $\bar{q}$ are bounded by color flux string-like gluons g into a hadron; (b) the string may be stretched from q end to $\bar{q}$ via the g kink [2]

The string may then break repeatedly into color singlet system for as long as the invariant mass of the string pieces exceed on-mass-shell hadrons.

Particle generator Pythia uses Quark Parton Model (QPM) to generate and perform hadronisation of particles for input to Monte Carlo package customized for a detector in experimental particle physics. The events simulated and observed were run concurrently, and were then fed into a physics analysis software to extract correction factor for the events.

Figure 3 shows the Feyman diagram of electron-proton interaction during the an electron-proton beam collision. In the deep inelastic scattering (DIS) process, quarks within the proton structure were ejected after interaction with virtual photon emitted by the incoming electron. The hadronisation of quarks and antiquarks into bounded state mesons and baryons could be model by the Quark Parton model (QPM) and the Lund String Model.

Hadronisation of free quarks occur just after collision process may result in the formation of heavy quarks such as baryon Λ which may decay into $\Lambda \rightarrow p^{+}\pi^{-}$ or $\Lambda \rightarrow n\pi^{0}$. The reconstruction of mass of Λ requires the mass of its daughters i.e. $p^{+}, \pi^{-}, n, \pi^{0}$ to be reconstructed from the momenta and directions of these daughter products.

In the neutral strangeness production study, the inclusive production of neutral strange particle to provide insights to the fragmentation process of $\Lambda, \overline{\Lambda}, K_{S}^{0}$ in the *ep* collision [3]. The advantage of using $\Lambda \rightarrow n\pi^{0}$ channel is that the study of CP (Conjugate and Parity) could be carried out using the radial distribution of neutral particles where charges of both mother and decay products were conserved – only the states changes involve i.e. (uds) in Λ to (udd) in n and $(u\bar{d})$ in π^{0}. In 1947, when the process of $\Lambda \rightarrow n\pi^{0}$ was first observed, the fact that Λ has much longer life time (i.e. $10^{-10}s$) than expected ($10^{-23}s$) due large mass and large production cross section.

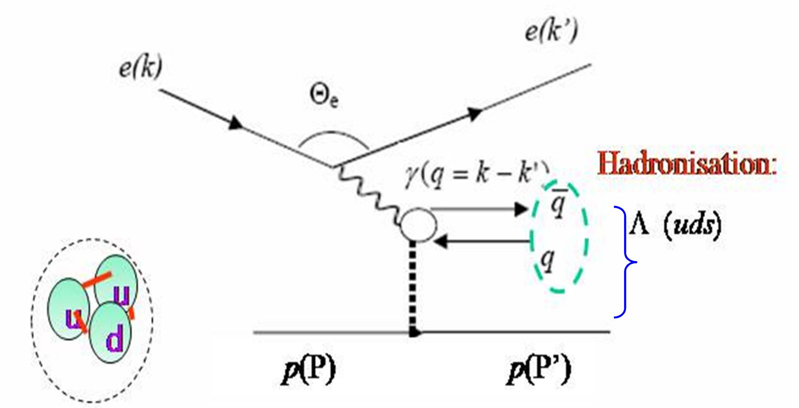

Figure 3. Kinematic variables in the electron-proton collision, with P, K, q as the momentum of proton p, electron e and photon γ (generated in the process) respectively.

This observation lead to the term "strangeness conservation" where the baryon Λ preserve the strangeness number *S* = -1, in such a way that strange quark *s* must be transformed in a process that can only occur through weak interaction that leads to longer life time. **Table 1** gives the components of $\Lambda \to n\pi^0$ channel.

Table 1 Components of $\Lambda \to n\pi^0$ channel

Decay scheme	$\Lambda \to n\pi^0$		
particle	Λ	n	π^0
Quark components	uds	udd	$\frac{\bar{u}u + \bar{d}d}{\sqrt{2}} \approx u\bar{d}$
Strangeness	-1	0	0
$I(J^P)$	$0\left(\frac{1}{2}^+\right)$	$\frac{1}{2}\left(\frac{1}{2}^+\right)$	
$I^G(J^{PC})$			$1^-(0^{-+})$

C : charge conjugation, *P*: Parity, *G*: parity on whole multiplet

KINEMATICS

A high energy neutral hadron-*i* with energy E_i, momentum p_i and mass m_i could be related by the following special relativity relation,

$$E_i^2 = m_i^2 + p_i^2$$

(3)

In case of photon, $p_i = E_i$ the mass ~0. Assuming that a neutral hadron E_i in the final state states propagate in the same manner as photon, therefore the momentum of a neutral hadron with energy and makes a polar angle θ_i with the z-axis and azimuthal angle ϕ_i with the x-y plane (refer to Figure 4), could be approximated by the following :

Momentum in x-direction: $p_{xi} = E_i \sin\theta_i \cos\phi_i$ (4)

Momentum in y-direction: $p_{yi} = E_i \sin\theta_i \sin\phi_i$ (5)

Momentum in z-direction: $p_{zi} = E_i \cos\theta_i$

Momentum $p_i = \sqrt{(E_i \sin\theta_i \cos\phi_i)^2 + (E_i \sin\theta_i \sin\phi_i\ )^2 + (E_i \cos\theta_i)^2}$ (6)

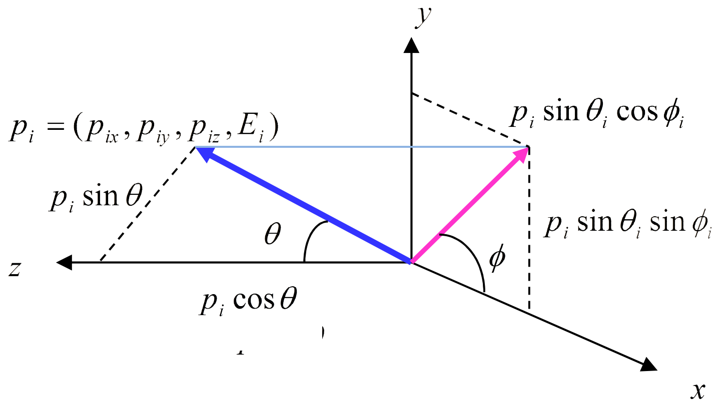

Figure 4. Direction of a particle with four-momentum $p_i = (p_{xi}, p_{yi}, p_{xi}, E_i)$, with z-axis positive in the direction of the proton beam, x-axis positive in the accelerator ring direction.

The above approximation particularly is useful to construct the momenta and direction of a neutral hadron in its final state such as Λ, π^0, n where there is lack of information on the particle tracks by the tracking detector, but has only available energy deposited in the calorimeter of the detector. Using the

Assuming that the particle-i with energy E_i travel towards the calorimeter of the detector and deposits its energy along the trajectory. As the momentum p_i of object-i is proportional to its E_i, therefore the components of p_i in x, y and z-axis would also be proportional to its energy E_i, the transverse momentum is reduced to [6]:

$$p_T = \sqrt{p_x^2 + p_y^2} = \sqrt{(E_T \cos\phi)^2 + (E_T \sin\phi)^2} \approx E_T = E \sin\theta \tag{7}$$

Thus the kinematic variables of the object-i traveling close to the speed of light and exist in the final states, in terms of the momentum components (p_{xi}, p_{yi}, p_{zi}) and energy E_i, could be written as the following [15],

(i) The momentum p_i of object-i, in terms of energy deposit E_i, polar angle θ_i and cosine azimuthal angle $\cos\phi_i$ of object-i [15], (by assuming that $p_i = E_i$ in the case of photon),

$$p_{xi} = E_i \sin\theta_i \cos\phi_i \tag{8}$$

$$p_{yi} = E_i \sin\theta_i \sin\phi_i \tag{9}$$

$$p_{zi} = E_i \cos\theta_i \tag{10}$$

$$p_i = \sqrt{(E_i \sin\theta_i \cos\phi_i)^2 + (E_i \cos\theta_i \sin\phi_i)^2 + (E_i \cos\theta_i)^2} \tag{11}$$

(ii) Transverse momentum of object-i;

$$p_{Ti}^2 = p_{xi}^2 + p_{yi}^2 = E_i(\sin\theta_i \cos\phi_i)^2 + (E_i \sin\theta_i \sin\phi_i)^2 \tag{12}$$

(iii) Invariant mass of object-i,

The invariant mass of the hadronic in the final state, from its measured four-momenta, is given by

$$mass_i = \sqrt{E_i^2 - p_{xi}^2 - p_{yi}^2 - p_{zi}^2}$$

[13].

Substituting **Equations (8), (9)** and **(10)** into this equation would give the invariant mass of object-i, in terms of is energy, azimutal and polar angles as:

$$mass_i = \sqrt{E_i^2 - (E_i \sin\theta_i \cos\phi_i)^2 - (E_i \sin\theta_i \sin\phi_i)^2 - (E_i \cos\theta_i)^2} \tag{13}$$

Equation (13) above uses photon characteristic of energy dissipation $E_i = p_i$ along its trajectory, with photon mass as zero. For neutral hadrons dissipating its energy in the same manner as photons, **Equation (8), (9)** and **(10)** could provide an approximation to its momentum in the x, y and z directions while the invariant mass remains as non-zero.

SUMMARY

In reconstructing the mass of neutron hadrons using the four-momenta and direction of the hadrons are particularly difficult where there is lacking of information of the tracks of neutral hadron traversing the detector. The momentum of neutral hadron in the final state such as baryons Λ, n and meson π^0 could be approximated by the relation $p_i = E_i$ the when mass of photon ~0. These neutral hadrons in the final may propagate in the same manner as photon i.e. traversing straight forward from its inception point but with their mass not equivalent to zero.

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