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Kaons and Quark Gluon Plasma

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The relative multiplicity abundance K^+/π^+ and K^+/p^+ arising in quark-gluon plasma formed in high energy nuclear collisions is determined. It is shown how these ratios assist in discriminating between various reaction channels.

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1. *Introduction*

The primary aim of experiments involving colliding nuclei is the discovery of the new state of matter consisting of quarks and gluons [1]. From the point of view of its detection, an important distinction of this quark gluon plasma (QGP) from the normal form of hadronic matter made of undissolved hadrons, viz hadronic gas (HG), is the appearance of numerous gluons. Gluons carry, aside from spin, only colour, the strong interaction charge, and hence their detection in an experiment can only be indirect, as colour is confined. However, the numerous gluons are very efficient in generating strange quark pairs in QGP [2]. The reactions depicted in Fig 1a can saturate the available phase space within $\sim 2\cdot 10^{-23}$ sec, while quark based reactions, Fig 1b, need typically 10 times this time. Since QGP is expected to be a high pressure state, its lifetime after formation has been estimated to be less than $2\cdot 10^{-23}$ sec. Consequently, observation of an anomalously large strangeness abundance may be taken as the observation of the gluonic degrees of freedom in the plasma.

The density and total number of strange quarks in the plasma has been proposed as a characteristic plasma signal on several occasions [3]. However discussion has focused on the observation of rare antibaryons. A much simpler, though less characteristic (as we shall see), experiment would only focus on the observation of kaons. The purpose of this communication is to determine the precise magnitude of the expected effect of QGP formation, defined at CM-energies of ~4 GeV/Nuc, on the Kaon abundance. We will focus here on the abundance of K^+ $= \bar{s}u$ for the following two reasons: 1) the $K^\circ = \bar{s}d$ neutral Kaon is not an eigenstate and K_o $-$ $\bar{K}_o$ oscillates, wiping out the $\bar{s}$-quark signal. 2) Kaons containing an s-quark ($K^- = s\bar{u}$, $K^o = s\bar{d}$) have a large strangeness-exchange cross section and their population will be representative of the late stages of the HG phase into which the plasma will transform during the evolution of the system. [4]

It is very likely that about half of the $\bar{s}$ quarks from the plasma will be used in making K^+-mesons, the other half contributing to the $K^o \pm \bar{K}^o$ states, and a smaller, and for this consideration, insignificant number of $\overline{s}$ quarks being contained in the anti-strange baryons; $\overline{sss}$, $\overline{ssq}$, $\overline{sqq}$, or $\overline{s}s$ mesons, as it is self-evident that such states have a much smaller chance of emerging from a baryon-rich plasma than does a $\overline{s}q$-meson. A further positive aspect of baryon rich plasma is the depletation of anti-baryons, which have the capacity, through strangeness-exchange reactions, to deplete the $\overline{s}q$ meson abundance. Though cross sections for such processes, e.g.,

$$\overline{s}q + \overline{qqq} \rightarrow \overline{sqq} + (\overline{q}q)_{\pi} \tag{1.1}$$

are large and they are highly exothermic, they will nevertheless proceed very slowly if anti-baryons are rare, as will be the case due to $\overline{q}$-suppression in baryon rich QGP [3].

From this discussion we are thus led to conclude that the K^+-abundance will be a significant measure of the properties of QGP. However, QGP events are expected in central nuclear collisions, which are defined in terms of high particle multiplicity. This introduces a bias, as a minimum multiplicity trigger will always be a minimum K^+ abundance trigger. Thus only abundance ratios, such as K^+/π^+, K^+/p^+, will be significant. We have selected equal charges here in order to minimise leading particle effects and other non-QGP distortions arising from normal hadronic processes. The ratio K^+/K^- is, as already mentioned, a measure of the properties of the hadronic gas at the freeze out condition [4].

The ratio K^+/π^+ will however show a much less dramatic rise than would be expected from the K^+-mesons alone. This is because pions, being the 'cheapest' carriers of entropy, will be copiously produced in the QGP to HG phase transformation. The plasma state contains a high entropy density in part due to the strong gluon component. An easy way to compute the π^+ abundance is to divide the entropy excess in GQP (excess over entropy of residual baryons) and divide it by the entropy carried by each pion [5] which will be, as we shall see, nearly 4 units (k = 1). The K^+/p^+ ratio will depend on the baryon content of the plasma and the calculations below will serve to determine the conditions under which a baryon-rich plasma will be formed.

In the following sections we discuss in turn the entropy content of the plasma, the K^+/π^+ and K^+/p^+ ratios followed by brief summary and outlook.

2. *Entropy in High Energy Nuclear Collisions*

Though it is practically impossible to derive the pion abundance arising from all individual processes in nuclear collisions, we can reliably estimate the dominant pion multiplicity component arising from QGP by considering the entropy content of the plasma [5].

We begin by recalling that the entropy density, σ, in an equilibrated system is related to pressure P, energy density ϵ, and baryon density ν, by the standard thermodynamic relation (see e.g. Ref [1]):

$$\sigma = \frac{S}{V} = \frac{1}{T}(p + \epsilon - \mu\nu) \tag{2.1}$$

where μ and T are the statistical variables, the baryochemical potential and temperature. Since the light quarks and gluons form a relativistic gas, we have for their respective pressure and energy density P_{qg}, ϵ_{qg}, noting the bag term B:

$$P = P_{qg} - B \tag{2.2a}$$

$$\epsilon = \epsilon_{qg} + B \tag{2.2b}$$

$$P_{qg} = \frac{1}{3}\epsilon_{qg} \tag{2.2c}$$

$$P = \frac{1}{3}(\epsilon - 4B) \tag{2.2d}$$

Making use of eq (2.2) in eq (2.1) we find that the entropy per unit of energy becomes

$$S_E \equiv \frac{S}{E} = \frac{\sigma}{\epsilon} = \frac{1}{T}\left[\frac{4}{3}\left(1 - \frac{B}{\epsilon}\right) - \mu(\nu/\epsilon)\right] \tag{2.3}$$

where the energy per baron E/b in the plasma appears.

$$E/b = \epsilon/\nu \tag{2.4}$$

So far the discussion has been pretty general—let us now assume that the total energy retained in the baryon rich plasma would be 1.5 GeV/fm^3, that the baryon density would be 3 ν_0 = 0.5 baryon/fm^3, which means that the energy per baryon would be 3 GeV/baryon. Such a situation seems to be a likely scenario in 4 GeV/Nucleon/$_{CM}$ nuclear collisions. We further take 4B ~

0.5 GeV/fm^3, as is indicated by recent study of hadronic spectra [6]. Furthermore we choose a fixed value $\mu_q = \mu/3 \approx T$ (which actually should be determined from the equations of state, but the error here is of negligible importance). When inserted in eq (2.3) we then find for $T \approx 160$ MeV

$$S_E \approx 6.6/\mathrm{GeV}$$

and similarly we find for the entropy per baryon

$$S_b = S/b = S/E\ E/b = 20$$

As each baryon carries $m_N/T_F = 7$ units of entropy out of the collision (see eq (2.9)), where $T_F \sim 140$ MeV is the freeze-out temperature, the remaining 13 units of entropy have to be distributed among pions and Kaons (here entropy of s-quarks, not counted yet, will be absorbed). We will show, cf eq (2.8), that each pion will contain 4 units of entropy; thus we expect in the described circumstances $\sim$3 pions for each baryon. Thus we expect that for a full-fledged quark-gluon plasma event in a U-U collision that up to 2000 particles will emerge. This is consistent with energy conservation arguments, which assign 1.2 GeV to each baryon and 0.5 Gev to each pion, with 0.3 GeV/baryon for strangeness excitation: 1.2 GeV + 3 $\times$ 0.5 GeV + 0.3 = 3 GeV/baryon. We have neglected in these qualitative considerations the entropy generation at the phase transformation boundary between QGP and HG. It is needed, at the level of 20-25%, in order to increase the entropy per energy from 6.6/GeV to above 8/GeV, in order to permit pionisation of the available energy at the rate of 4 units per 0.5 GeV pion.

We now obtain the quantitive numbers that support the above qualitative discussion. The entropy associated with each pion is calculated assuming a dilute ideal pion gas at a given temperature. The partition function is:

$$\ell n Z_\pi = -V g_\pi \int \frac{d^3p}{(2\pi)^3}\, \ell n \left(1 - \lambda_\pi\, e^{-\beta\sqrt{p^2 + m_\pi^2}}\right), \tag{2.5}$$

where $\beta = 1/T$, $g_\pi = 3$ for the three isospin states, and V is the volume of the gas. The fugacity $\lambda_\pi \rightarrow 1$ has been introduced to facilitate the determination of the pion multiplicity N_π:

$$N_\pi = \left[\lambda_\pi \frac{\partial}{\partial \lambda_\pi} \ln Z_\pi\right]_{\lambda_\pi = 1} = V g_\pi \int \frac{d^3p}{(2\pi)^3} \frac{1}{e^{\beta\sqrt{p + m_\pi^2}} - 1} \,. \tag{2.6}$$

The entropy is,

$$S_\pi = \frac{\partial}{\partial T}\left(T \ell n Z_\pi\right) \tag{2.7a}$$

$$= \ell n Z_\pi + V g_\pi \frac{1}{T} \int \frac{d^3p}{(2\pi)^3} \frac{\sqrt{p^2 + m_\pi^2}}{e^{\beta\sqrt{p^2 + m_\pi^2}} - 1} \,. \tag{2.7b}$$

and we recognise the two first terms of eq (2.1) here. It is easy to verify that in the Boltzmann approximation but with the limit $m_\pi/T \to 0$, the specific entropy per pion has the limit,

$$S_{N_\pi} = S_\pi/N_\pi \to 4 \,. \tag{2.8}$$

However keeping the Bose-statistics for $m_\pi/T \to 0$ limit we find analytically $S_{N_\pi} \to 2.92$. Thus it is not surprising that for $T \sim m_\pi$ one finds

$$S_{N_\pi} = \begin{cases} 4.1 & T = 160 \text{ MeV} \\ 4.025 & T = 180 \text{ MeV} \end{cases},$$

and we conclude that each pion comes away with 4 units of entropy from the plasma.

From eq (2.7b) and (2.6) we estimate the entropy per nucleon:

$$N_n = V g_N \int \frac{d^3p}{(2\pi)^3} \frac{1}{e^{\beta\sqrt{p^2 + m_\pi^2}} + 1} \,. \tag{2.9a}$$

$$\frac{S_N}{N_N} \approx \frac{m_N}{T} \tag{2.9b}$$

where eq (2.9b) reflects on the fact that $m_N >> T$ (cf eq (2.7b)). Thus each nucleon carries $\sim m_N/T_F \sim 7$ units of entropy, for a freeze out temperature of 140 MeV. This value is slightly higher than that estimated for nuclear collisions at 2 GeV/Nuc [7].

3. *Kaon to Pion Ratio in Nuclear Collisions*

We first observe [3] that in the plasma, the strange quark density nearly saturates the phase space.

$$n_s \equiv \overline{s}/V = g_s \int \frac{d^3p}{(2\pi)^3} \frac{1}{e^{\beta\sqrt{p^2 + m_s^2} + 1}} \,. \tag{3.1a}$$

where $g_s = 6$ for two spin and 3 colour degrees of freedom and m_s, the strange quark current

(Lagrangian) mass is ~180 MeV [6]. Expanding eq (3.1a) in a series we find

$$n_s = \frac{3}{\pi^2} T^3 \sum_{n=1}^{\infty} \frac{(-)^{n-1}}{n^3} W(n\, m_s/t) \tag{3.1b}$$

where

$$W(X) = X^2 K_2(X)$$

The saturated strange quark density is now easily determined:

$$n_s = \begin{cases} 0.24/\mathrm{fm}^3, & T = 160\ \mathrm{MEV} \\ 0.35/\mathrm{fm}^3, & T = 180\ \mathrm{MeV} \end{cases} \tag{3.2}$$

Recalling here our estimate that the typical baryon density reached in a nuclear collision at (3 GeV/Nuc)$_{CM}$ energy deposited would be ~0.5/fm^3, we find that the important abundance ratio, strangeness per baryon, n_s/b is ~0.7. Therefore

$$n_s/\pi = n_s/b \cdot b/\pi = 0.7 \cdot \frac{1}{3} \approx 0.25 \tag{3.3}$$

We are interested in the K^+/π^+ ratio, and it is easy to see that 1/2 of the s quarks will be bound in K^+ mesons, the other half in neutral Kaons. Concerning the π^+ fraction of the π abundance, we must also consider the proton-neutron asymmetry in heavy nuclei. Noting that 2/3 of u quarks becomes π^+ while 1/3 goes to π^o we find that

$$\pi^+/\pi = \frac{2}{9} + \frac{1}{9}\left(\frac{2Z}{A}\right) \underset{\frac{2Z}{A}\to 1}{\longrightarrow} \frac{1}{3} \tag{3.4}$$

Hence

$$K^+/\pi^+ = \frac{1}{2}\, n_s/\pi^+ = \frac{1}{2}(n_s/\pi)(\pi/\pi^+) \approx 1.6 \times 0.25 \approx 0.4$$

It is worth recording here that the additional entropy required to make the large $\bar{s}q$-Kaon multiplicity—as shown above $\bar{s}q/b \gtrsim 1/2$—is mostly contained in the strange quark gas which we have not counted when estimating the entropy content of the plasma. Furthermore, strangeness also contributes, but not essentially, to the plasma energy density. Finally, one should be wary that the strangeness abundance does not saturate the entire available phase space. The actual correction factor is [3]

$$f = \tan h\,(t/\tau)$$

where $\tau \approx 2 \times 10^{-23}$ sec is the strangeness equilibration constant and t is the plasma life time. Expecting $t \sim \tau$, the likely value for f may be 3/4. While we disregard f from further considerations below, all our expectations concerning $\overline{s}$ or K^+ abundance should be reduced by this factor.

These considerations can be made slightly more precise by actually evaluating, at given T and μ, the expression:

$$\frac{K^+}{\pi^+} = \frac{1}{2}\left[\frac{2}{9} + \frac{1}{9}\left(\frac{2Z}{A}\right)\right]^{-1} \frac{S_{N_\pi}}{V(\sigma - (S_N/b)\nu)} V n_s\,, \tag{3.5}$$

where as previously, n_s, σ, ν, are the densities of strange quarks, of entropy and of baryons respectively. The entropy and baryon density in the perturbative plasma is well known (c.f. [1]):

$$\nu = \frac{2}{3\pi^2}\left(1 - \frac{2\alpha_c}{\pi}\right)\left[\left(\frac{\mu}{3}\right)^3 + \left(\frac{\mu}{3}\right)\left(\pi T\right)^2\right], \tag{3.6a}$$

$$\sigma = \frac{2}{\pi}\left(1 - \frac{2\alpha_c}{\pi}\right)\left(\frac{\mu}{3}\right)^2(\pi T)$$

$$+ \frac{14}{15\pi}\left(1 - \frac{50}{21}\frac{\alpha_c}{\pi}\right)\left(\pi T\right)^3 + \frac{32}{45\pi}\left(1 - \frac{15}{4}\frac{\alpha_c}{\pi}\right)\left(\pi T\right)^3, \tag{3.6b}$$

where the last term in eq (3.6b) refers to the gluon degrees of freedom. α_c is taken here as $\sim$0.5.

The pion number in eq (3.5) is obtained by calculating the entropy contained in the plasma ($V\sigma$), subtracting from it the entropy carried away by the baryon number and dividing by the entropy per pion, eq (2.8). The entropy per baryon (2.9b) taken to be 7 and 2Z/A = 1. As can be seen from the results presented in Fig 2, K^+/π^+ ratio varies little with μ and is $\sim$0.4 at $\mu = 3T$, the case we have discussed qualitatively. Furthermore, the dominate T-dependence, or T^3 factor drops out in eq (3.5) leaving an almost T-independent K^+/π^+ ratio.

In p-p collisions of comparable energy this ratio is below 0.1 [8]. Consequently we suggest the measurement of the K^+/π^+ ratio as function of multiplicity and expect a rise by a factor three as the multiplicity moves to high values associated with the quark-gluon plasma. It is important to sum the transverse momentum pions and kaons to account for their different expected temperatures—pions are 'cooled' by rescattering during the hadronic gas expansion phase while the weakly interacting kaons reflect earlier higher temperatures. However, rapidity should be kept as a variable, indicating where plasma formation has occurred.

4. *Kaon to Baryon Ratio in Quark-Gluon Plasma*

It is likely that depending on the energy and atomic number, A, of the colliding nuclei, there will be different domains in rapidity space involving: 1) baryon rich; 2) baryon poor plasma; or 3) no plasma at all. Since the abundance of K^+ is independent of baryon number density, on the hypothesis that it reflects the gluon density via s quarks, it seems that the ratio K^+/p^+ will be a useful measure to distinguish the three regions mentioned above. We have

$$\frac{K^+}{p^+} = \frac{1/2}{Z/A}\frac{\bar{s}}{b} = \frac{1}{(2Z/A)}\frac{n_s}{\nu} \qquad (4.1)$$

and the required quantities are given in eq (3.1) and eq (3.6a). For $T \sim m_s$ we find that the n = 2 term in eq (3.1) reduces the Boltzmann term by ~8%. With W(1) = 1.625, and changing slowly, we have:

$$n_s \approx 0.45\, T^3 , \qquad (4.2)$$

and hence,

$$\frac{K_+}{p^+} \approx 11 \Big/ \left\{ \left(\frac{\mu}{3T}\right) \pi^2 + \left(\frac{\mu}{3T}\right)^3 \right\}. \qquad (4.3)$$

This ratio shown in Fig 3 as a function of μ is quite sensitive to a variation in μ, when $\mu < 600$ MeV. It is unlikely that $\mu > 600$ MeV is explored in quark-gluon plasma forming nuclear collisions, as this would lead to quite enormous baryon and energy densities at $T \gtrsim 150$ MeV.

Thus we conclude this brief section noting that a measurement of the K^+/p^+ ratio as function of rapidity would provide a qualitative measure to the distribution of the baryon number in plasma. This information is not provided by π^+/p^+ since pions are neither characteristic of the plasma, nor are they *in principle*, as $\bar{s}$ quarks are, insensitive to the values of the baryo-chemical potential, or said differently, to the baryon density of the plasma.

5. *Summary and Outlook*

We have discussed here the K^+ mesons emerging as messengers of the quark-gluon plasma in nuclear collisions. We have shown that a mild enhancement of the K^+/π^+ multiplicity ratio may be expected leading to a rise by a factor of three in this ratio as function of multiplicity, if a quark-gluon plasma is formed. Here the hypothesis is that low multiplicity collisions are similar to p-p collisions, while quark-gluon plasma formation is accompanied by *high* particle multiplicity.

It has been argued previously that a quark-gluon plasma may be created in relativistic nuclear collisions both in baryon rich and baryon poor forms, the latter being expected in the central rapidity region at ultrarelativistic energies, the former in moderate energy very heavy ion nuclear collisions, say U on U at $(5\ \mathrm{GeV/Nuc})_{CM}$ also at central rapidity. Since the high absolute abundance of K^+ is independent of baryon density, viz baryochemical potential in the plasma, it is possible by studying simultaneously the K^+ and p^+ abundance to determine the baryon number content of the plasma as a function of e.g., rapidity. To fascilitate this study we have computed the relative K^+ to proton abundance as function of baryochemical potential and have shown that in the baryon rich plasma this ratio would be near to unity. We should remember that part of the p^+ abundance may be in the form of strange baryons, since reactions such as

$$qqq + s\bar{q} \rightarrow sqq + (q\bar{q})_\pi$$

are exothermic and cross sections are quite substantial. Consequently strange baryons must be carefully counted. Calculations in the hadronic gas [4] indicate that, depending on the chemical potential, freeze out hyperons could indeed be more numerous than $s\bar{q}$ (K^-) mesons. However interesting, such behaviour is characteristic of a hadronic gas, not of quark-gluon plasma which must be studied through observation of antistrange quark content of hadrons.

Here perhaps the most characteristic and promising avenue, though difficult experimentally, seems to be the study of strange and multistrange antibaryons [3]. E.g. in a quark recombination model the $\overline{\Lambda}/\overline{p}$ abundance would follow the $\overline{s}/\overline{q}$ abundance ratio at the phase transition, which at $\mu \sim 500$ MeV, T $\sim 1/3\ \mu$ would make $\overline{\Lambda}$ more abundant than $\overline{p}$, a quite unlikely circumstance in the hadronic gas phase. Similarly significant may be the observation of $\overline{ss}$ clustering in anti-cascades which in the hadronic gas phase has a relative probability of 10^{-3} at $\mu \sim$ 500 MeV (with reference to single-$\overline{s}$ hadrons) [9], while in quark gluon plasma it is 10^{-4}.

It seems that strangeness, as a signal of the quark gluon plasma, is alive and well.

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Figure Captions

Fig. 1: Strangeness generating processes in quark-gluon plasma: a) glue-glue b) $q\bar{q}$ driven processes.

Fig. 2: K^+/π^+ ratio from quark-gluon plasma at T = 160 and 180 MeV, as function of baryo-chemical potential μ (m_s = 180 MeV), α_c = 0.5, 2Z/A = 1).

Fig. 3: K^+/p^+ ratio from quark gluon plasma same parameters as Fig 2.

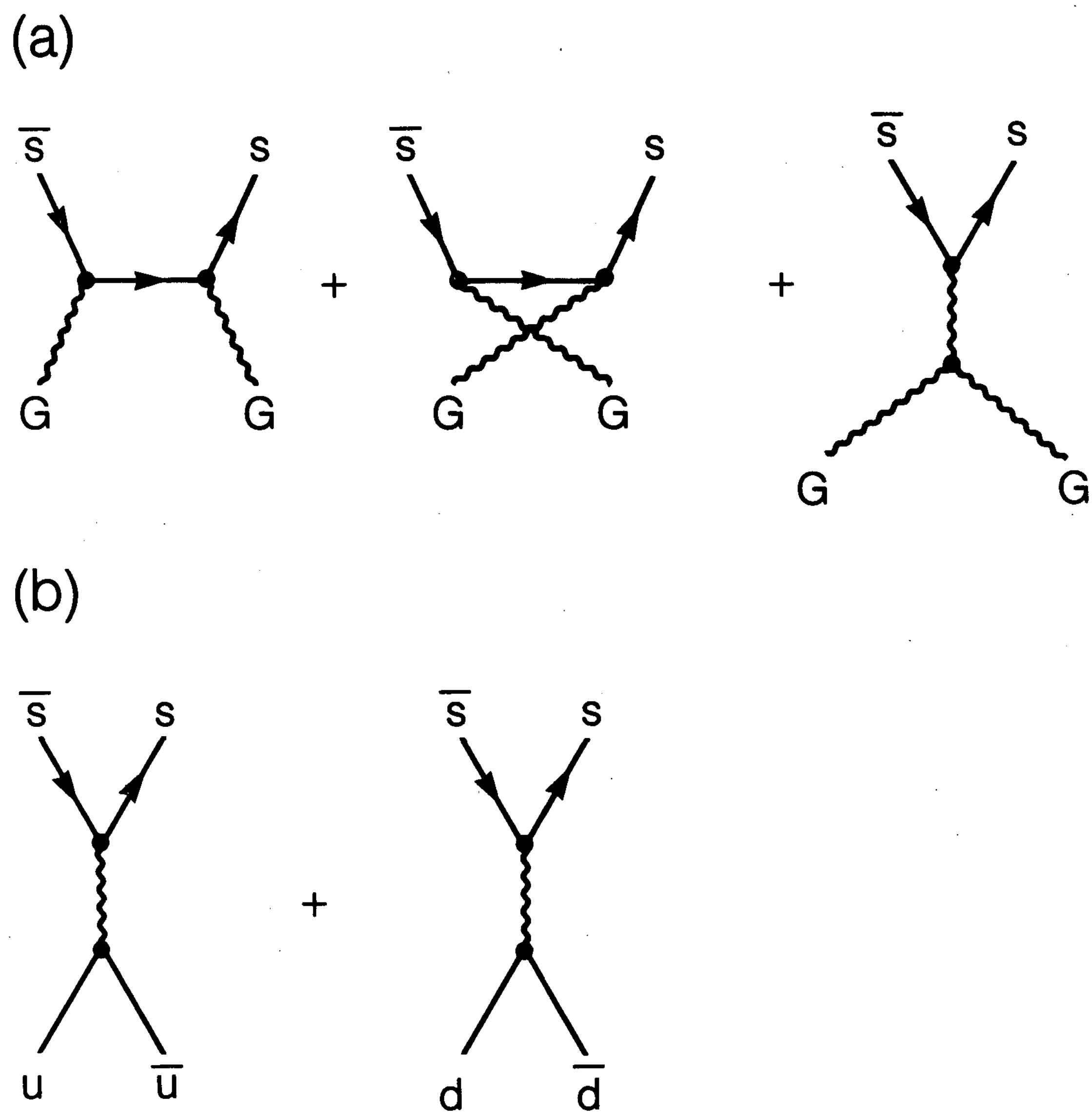

Fig. 1

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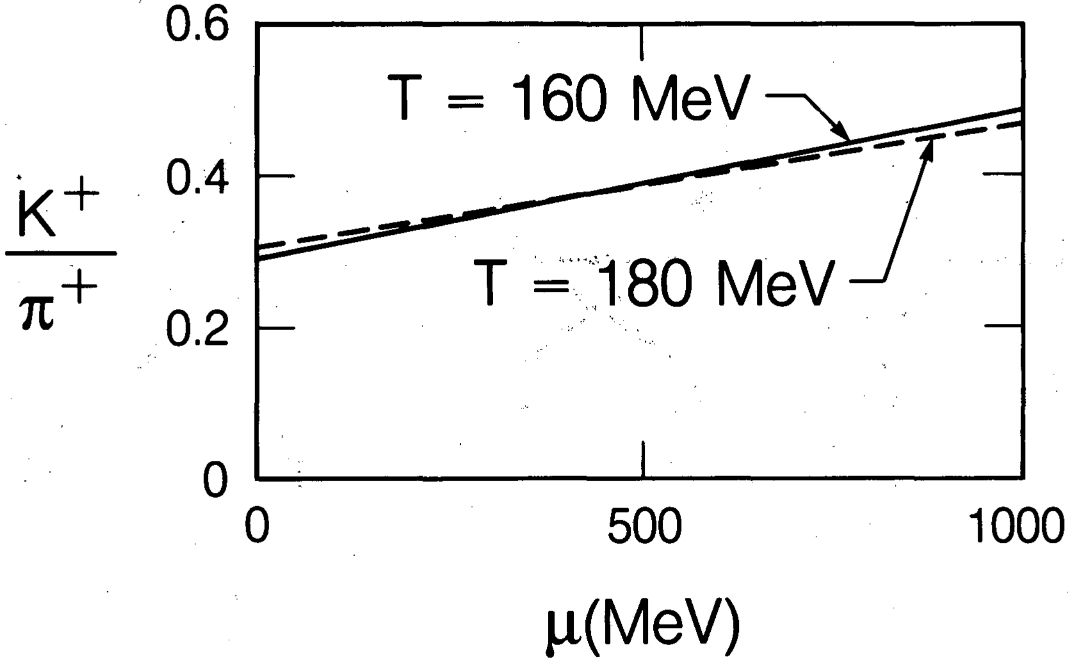

Fig. 2

XBL 846-2473

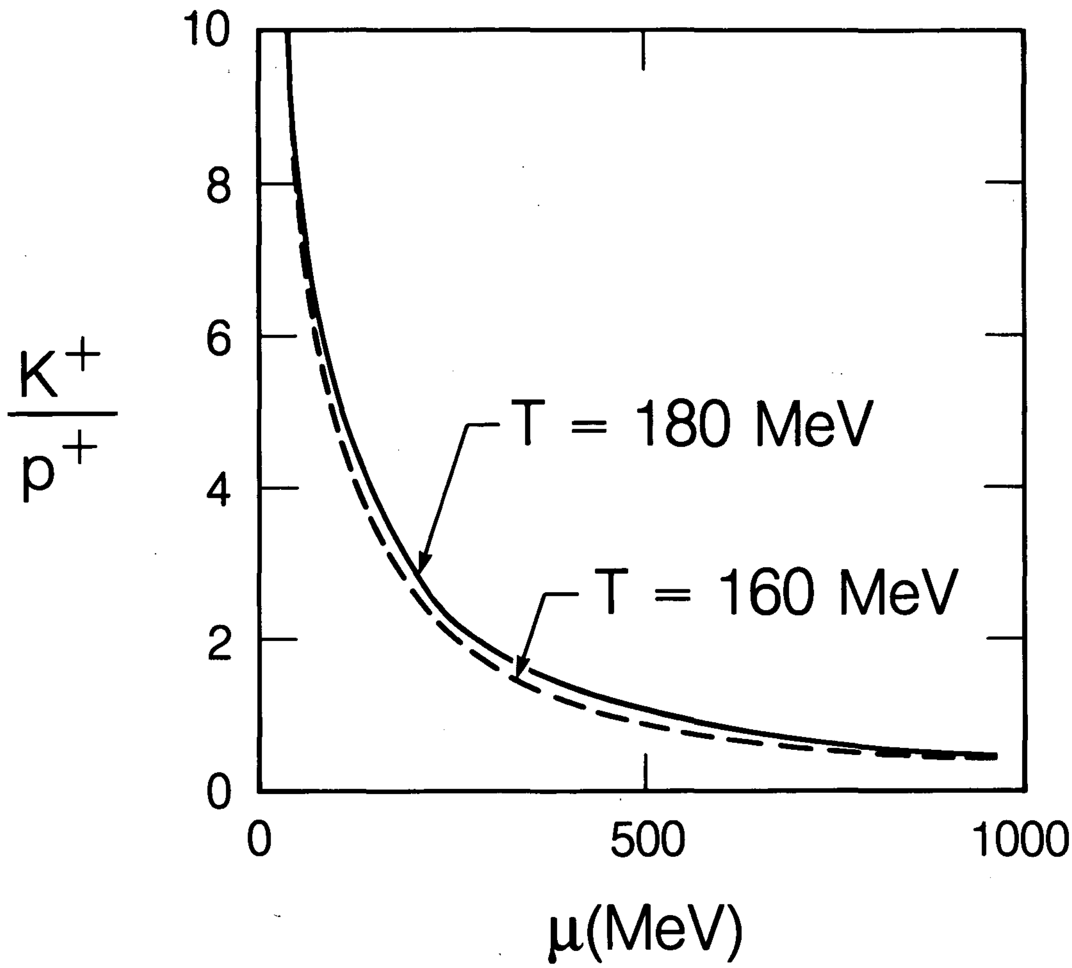

Fig. 3

XBL 846-8977

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