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Search for rare quark configurations at RHIC

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1. The H-Dibaryon, a possible QGP signature

It was suggested early on, by Jaffe [1], that in the bag model a six quark bag (uuddss, S=-2) may exist, based on the fact that the color magnetic forces are attractive and thus allow the groundstate of this configuration to be below the ΛΛ mass (2230 MeV). If so this configuration, called the H-Dibaryon, might be stable against strong decay and could have a considerable lifetime. Jaffe's theory was corroborated recently by lattice gauge calculations [2]. An event that could be interpreted as an H-Dibaryon was reported by Shahbazian et al. [3] in a high energy proton-propane interaction. The event showed a characteristic Σ^-p weak decay, but the subsequent $\Sigma^- \rightarrow \pi^-$n decay could not be detected so that the interpretation remains inconclusive. On the other hand taking the combined experimental output of emulsion measurements from the last three decades, we are faced with three possible double strange hypernuclei [4,5,6]. The most publicized case was the event observed by Prowse [5] in 1966. In an emulsion experiment two consecutive πp- branches were seen emerging from the same source, leaving an α particle behind. The data were attributed to the following decay

$$ {}^{6}_{\Lambda\Lambda}He \rightarrow \pi^- + p + {}^{5}_{\Lambda}He \qquad (1) $$

$$ {}^{5}_{\Lambda}He \rightarrow \pi^- + p + \alpha \qquad (2) $$

On the other hand it was argued that if the H exists and is stable against strong decay, the branch

$$ {}^{6}_{\Lambda\Lambda}He \rightarrow H + \alpha \qquad (3) $$

should be populated.

But the existence of the ΛΛ hypernucleus decay, as in (1), does not entirely exclude the existence of an H-Dibaryon. The argument is only valid if the lifetime of the H is sufficiently longer than a lifetime based on strong decay. The closer the H-mass gets to the ΛΛ limit, the more comparable the two lifetimes become. In the mass range from 2130 MeV to 2230 MeV, τ_s is comparable to τ_w, so that weak decays with ΔS=1 are not excluded. The other alternative consistent with the double hypernucleus detection is a stable H ($m_H \leq m_{nn} \approx 1850$ MeV). Then the decay of the ΛΛ hypernucleus into H + α is highly suppressed by wave function effects [7]. Therefore, if the H has a smaller mass than the neutron-neutron ground state, a deuterium would decay, via a strong process into H and π^+. This decay was obviously never observed. Based on these

arguments it seems that the most promising mass window for an H-Dibaryon is from 2130 MeV to 2230 MeV.

Independent of plasma formation, a relativistic heavy ion reaction is perfectly suited for H production. The major advantage of H production in heavy ion collisions is the high luminosity of the beam (particle experiments use low luminosity K^- beams). The high incident energy allows for the production of strangeness in many parallel NN collisions. The probability for wavefunction overlap of strange single baryons is drastically increased and can be approximately scaled by the number of Λ's produced. The largest complication is the distinction of H decay particles from the debris of multibody final states, see chapter 3.

The search for the H-Dibaryon has triggered some considerable interest in the heavy ion community. Crawford et al. suggest an AGS experiment to search for the doubly charged decay $H \rightarrow \Sigma^- p$ with a high resolution TPC [8]. E864 [9] at the AGS is also exploring the H search and extends the mass range of Crawford's experiment by looking for the neutral particle itself, assuming that the emulsion experiments did not really exclude an H-Dibaryon that is stable against first order weak decays. At CERN, Pretzl et al. [10] suggested a heavy ion experiment that could look for strangelets and its smallest configuration, the H, by 1995. Based on this interest one should consider an H search for RHIC where in addition to the general formation by coalescence, an enhancement based on QGP formation is expected, see chapter 2.

It is worth mentioning that other models, like the Skyrme model, also allow for multi quark composites but predict different ground states. In the Skyrme model the H is not lighter than the $\Lambda\Lambda$ ground state, instead a $\Sigma^- \Sigma^-$ state which is stable against strong decay is predicted [11]. I will not discuss here the probability of reconstruction for this channel in STAR, but one should keep in mind that the $\Sigma^- \Sigma^-$decay is not reconstructible without neutral particle determination.

2. The yield of H Dibaryon production at AGS,CERN and RHIC

Dover et al. calculated yields for H-Dibaryon production at the AGS based on a coalescence model [12]. The coalescence model assumes that H's are formed by simple $\Lambda\Lambda$, $\Sigma\Sigma$, or ΞN fusion. The yield for the ΞN channel depends strongly on the baryon density. At the AGS, where full stopping was measured, higher ΞN contributions are expected. Fig.1 shows the relative importance of the $\Lambda\Lambda$, the $\Sigma\Sigma$ and the ΞN channel for H-Dibaryon production as a function of initial temperature. Based on the yield for Λ's at a certain incident energy one can calculate the expected H cross section, assuming that 50% of the Λ's originate from Σ decay, which allows a Σ yield calculation. So the overlap probability of the Λ wavefunctions determines the H cross section.

Based on the ARC code, which is in very good agreement with the Λ production at the AGS, Dover et al. calculated the production probability for H's at the AGS [13]. As soon as more than two Λ's are produced in one central heavy ion collision, there is a probability for baryon-baryon fusion. Taking all the known parameters into account (Λ cross sections from E810 [14]) the predicted abundances for H's in Si+Au and Au+Au collisions are shown in Fig.2. Fig.2 also compares the heavy ion production rate for H's (dN/dy = 0.1 at central rapidity) to the production rate for $\Lambda\Lambda$ hypernuclei in heavy ion

collisions. The ${}^{6}_{\Lambda\Lambda}He$ complex was the one attributed to the Prowse experiment in 1966. In a heavy ion collision its formation is suppressed by 5 orders of magnitude compared to the H production. Based on this model a detection of its successive Λ decays without a simultaneous H reconstruction in a heavy ion apparatus, as suggested by Crawford et al., would therefore exclude the existence of an H-Dibaryon.

Dover et al. also expanded their calculations to CERN energies [15]. NA35 [16] measured a Λ production yield of around 2.1 Λ's per unit rapidity for central collisions at central rapidity. Folding the yields for Λ and Σ into the calculation, Dover estimates a H yield of around 10^{-1} per unit rapidity, which is comparable to the AGS results in Fig.2. Fig.3 shows that from a certain baryon density on, the H cross section is nearly independent of baryon density. Increasing energy can only provide an increase in the initial temperature. For AGS and CERN energies, the measured slope parameters for baryons are comparable (around 180 MeV) so that no great change in H production is expected. Thus, provided that there is no plasma formation, we can expect a moderate increase in H formation from AGS, CERN energies to RHIC energies, due to the opposing effects of temperature and baryon density. QGP formation would change this picture drastically. In addition to a much higher initial temperature, a further difference between the simple coalescence model and a QGP production model can be attributed to enhanced H production due to 8c*8c cluster fusion at short distances. Cluster formation during hadronization of a plasma phase has been discussed in several publications [17,18]. The assumption is that close to a phase transition (coming from the QGP) the interactions favor certain color magnetic attractive quark configurations. Short range color correlations are allowed because color screening no longer favors hadronization into low mass hadronic states (e.g. pions) close to the boundary with hadronic matter (late stage of hadronization). Another difference between QGP H-production and simple fusion processes in hadronic fireballs is that emerging from the QGP the H can be treated as a Boltzmann particle, meaning it is produced in chemical equilibrium and remains in this state until freeze-out. The H abundance would then be as much as one order of magnitude higher than for the fireball case, see Fig.3.

For RHIC energies one can expect a cross section of 10-100 mb in Au + Au collisions. Therefore, depending on the QGP formation, the H might be more abundant than the antiproton. The yield per event is on the order of 1 to several 10 H's. A drastically increased H cross section can therefore serve as a QGP signature at RHIC.

3. Experimental search for the H Dibaryon at RHIC

A detection scheme for the H in heavy ion collisions at RHIC depends greatly on its mass and the subsequent decay modes. Each decay branch provides different challenges to the experimental setup. Assuming the weak decay of the H ($2m_n \leq m_H \leq 2m_\Lambda$), the most realistic decay mode seems to be the ΔS=l case, which results in a lifetime of 10^{-8} to 10^{-9} sec. This means that the H lives roughly one order of magnitude longer than the Λ. The most promising channel, then, is the ΣN-channel. Table I shows the possible decay modes of an H-Dibaryon based on its mass, Fig.4 shows the resulting lifetimes.

TABLE 1. Possible decay modes of the H.

Channel	Threshold mass (MeV/c^2)	ΔS
$\Lambda\Lambda$	**2231**	**0**
$\Lambda N\pi$	**2192**	**1**
$NN\pi\pi$	**2152**	**2**
ΣN	**2134**	**1**
Λn	**2055**	**1**
$NN\pi$	**2016**	**2**
nn	**1879**	**2**

The ideal case for STAR would be the Σ^-p-channel which is dominant in the mass range m_H=2134-2231 GeV/c^2. This double charged V-decay is perfectly suited for reconstruction by a SVT-TPC combination in a relativistic heavy ion experiment. Assuming the validity of the 3 $\Lambda\Lambda$ hypernuclei events, one can assume that the major branch goes into Σ^-p, with a subsequent decay of $\Sigma^-\rightarrow\pi^-$n [8]. The neutron cannot be detected, but the V would reveal a 'kink' after the original decay, which would make it distinguishable from simple two body decays. Assuming the 'kink' is detectable, a background caused by Λ and K_L decay could be distinguished. For the lifetime range mentioned above, the H would decay in the active SVT-TPC volume. Most Λ's would have decayed already. The Σ^- will decay roughly 10 cm after the first V. ΔS=2 would cause a lifetime of several days making the neutral H only detectable in a hadronic sampling calorimeter of high granularity. A high resolution measurement in a calorimeter could distinguish the H from a neutron, but it would still have to fight considerable antineutron background, which has roughly the same abundance as the H itself [19]. Although simulations of the STAR EMC response to hadrons are underway, I will not discuss the neutral H search here as a valuable option for STAR. It is actively pursued in E864 at the AGS.

4. Higher order strange quark composites

Michel [20] argued that the simplest stable complex in the quark model should be a spin-zero, uncharged B=6, S=-6 complex. This object would consist of all three colors of spin-up and spin-down u, d, and s quarks. Assuming stability against strong decay, an Ω^- capture in nuclear matter is proposed as formation process. Michel calls this particle a q_α state. Fig.5 shows a simulation assuming that the decay of this particle is a second order weak decay with a lifetime of several hours. This simulation for E887 at the AGS assumed a downstream sampling calorimeter equipped with timing readout, which allows simultaneous time of flight and kinetic energy measurements. The electromagnetic resolution of this detector (not folded into the simulation) is comparable to the planned STAR EMC. Assuming the hadronic response as well as the granularity allow unambiguous determination of the total energy of each particle hitting the calorimeter, a detection would be easy based on an invariant mass reconstruction that should yield

around three times the H-Dibaryon mass. In the mass range of 6 GeV, no background is apparent.

5. Composite objects with charm contribution

A possible pentaquark state was first postulated by Gignoux et al. [21]. This state with Baryon-number B=l contains one charm quark ($\overline{c}$suud). Gignoux predicts that this ΔS=l configuration is stable against strong decay, which leads to a lifetime that is comparable to open charm lifetimes ($\tau = 5*10^{-13}$ sec). The pentaquark (P^0) search was never pursued at AGS or CERN energies because of the small probability, of c production. The open charm production threshold is $\sqrt{s} = 5.61$ GeV. So all $D\overline{D}$ production at the AGS is subthreshold. But as Dover points out [22], the c production is much higher at $\sqrt{s} = 200$ GeV and is dominated by $D\overline{D}$ production and not by J/ψ production. From hadronic collisions [23,24] one gets a ratio of

$$\frac{\sigma\left(\pi^- p \rightarrow J/\psi\right)}{\sigma\left(\pi^- p \rightarrow c\bar{c}\right)} = 2.5*10^{-3} \qquad (1)$$

Fig.6 shows the dependence of the $D\overline{D}$ abundance on $\sqrt{s}$.

Mueller [25] and Shuryak [26] pointed out independently that the open charm production should be further enhanced in the RHIC regime. Mueller calls this phase, which emits mainly charmed quarks, the preequilibrium stage [25]. Shuryak [26] argues that in this stage the gluons are already equilibrated and emit thermal cc pairs from a hot glue source with a temperature of 450-500 MeV. This model does not require chemical equilibrium, and the following hadronization of quarks does not affect the open charm kinematics in any significant way. This means that the open charm is a.) enhanced (by factor 3 in Shuryak's model) and b.) will serve as a perfect thermometer for the initial stage of the plasma. The quarks are also thermally equilibrated (after about 0.3 fm/c) but the production of quarks is suppressed compared to the gluon production. Hence one is left with the initial quarks from the colliding nucleons. A rough estimate based on measured quark and gluon structure functions shows that at small x_F (RHIC environment), the overall yield of quarks is small and results in around 1 parton per nucleon. So around 400 quarks in the initial stage are expected, whereas the gluon production in the initial stage is enhanced to around 1000 gluons. Thus the ratio of gluons to quarks is inverted compared to the condition for chemical equilibrium. The main process for particle production is then gg into qq. Comparing the different fusion and excitation diagrams for cc production (Fig.7), the strongest contribution is therefore due to $gg \rightarrow c\bar{c}$. Because of the high temperature and the fact that the energy in the gg pair is around 3T (3*500=1.5 GeV), direct c-production (c-mass=1.5 GeV) is potentially feasible. Therefore, the open charm production is considerably enhanced. At the same time Shuryak postulates that the J/ψ yield is highly suppressed, mainly because of the small probability of the produced charm pairs to confine into the J/ψ groundstate if produced with high momentum. The above ratio should, therefore, decrease further in the case of a QGP.

Independent from QGP formation, we expect a considerable cross section for DD production. In RHIC pp collisions we estimate a yield of around 0.3 mb. Assuming a $A^{2\alpha}$ dependence with mass one gets

$$\sigma(Au + Au \rightarrow c\bar{c}) \approx A^{2\alpha}\, \sigma(pp \rightarrow c\bar{c}) \approx 1\ barn \tag{5}$$

In central collisions this yields at least one $D\overline{D}$ pair per event and unit rapidity. The problem in heavy ion reactions is, as in the case of the H, the reconstruction of the P^0 decay in a high multiplicity environment. Again, one has to choose a decay branch that only populates charged particles. Those applicable to the P^0 scheme are

$$P^0 \rightarrow K_S\, \Lambda \rightarrow \pi^+\pi^-\, \pi^-\, p \tag{6}$$

$$P^0 \rightarrow K_S\, K^-\, p \rightarrow \pi^+\pi^-\, K^-\, p \tag{7}$$

Only the neutral pentaquarks are suitable because the charged state decays into at least one neutral particle. P^0 will have a large momentum in the laboratory frame, and the secondary vertex should be comparable to the D-meson vertices. The SVT can detect particles with a secondary vertex from around a few hundred micron away from the primary. The tertiary weak decays of the K_s and the Λ's will occur sufficiently far from the secondary vertex. However, the branching ratio into these channels is on the order of 1%. Assuming a production rate of 1-2 orders of magnitude less than the D itself, we have a factor 250 suppression rate for the P^0 compared to the D^0. Based on the questionable effort to reconstruct the D^0 with the SVT, a pentaquark search seems very ambitious.

Edvard Shuryak recently suggested the idea to look for charmed baryons instead of the pentaquark state. Its lifetime is roughly a factor 2 shorter than the D^0 lifetime ($c\tau \approx 80\mu$). The Λ_c can be produced and is actually the major background in a D-yield determination by simple K reconstruction. Although the yield from pp collisions results in a factor 10-100 suppression of Λ_c compared to D production, the ΛK branching ratio of 22% enhances the reconstruction probability. We can then consider a 3 prong of (p π K) which is much more selective than the reconstruction of the (π π K) prong in the D-decay. The probability of a proton crossing with the previously determined K track, is very small due to the small baryon density in the central region.

In conclusion a prerequisite for the reconstruction of any charmed baryon configuration seems to be the successful reconstruction of the open charm at RHIC. Fig.8 shows a simple K reconstruction from 8.000 central Au+Au RHIC events. The tail can be attributed to the D-meson decay with an accuracy of 5-10%. This results in a successful D-yield reconstruction that does not reveal any background, making determination of the yield of D-production at RHIC feasible. But the kinematic parameters of the D (four momentum vector) cannot be determined without invariant mass reconstruction, requiring full reconstruction of the decay chain. As Shuryak pointed out, the slope of the momentum spectrum is of utmost interest since it monitors the initial stage of the reaction. If Shuryak's theory of a purely guonic phase with a temperature of 400-500 MeV is valid, then this measurement will reveal a difference to standard QGP models (Bjorken model assumes T=240 MeV at RHIC, T=290 MeV at LHC).

The simulation effort at Warsaw is aimed at reconstructing the two body decay of the neutral D's [27]. A three prong or even five prong branch for charged D mesons is possible and might be more selective, but is also reduced in efficiency based on acceptance and track reconstruction. Further studies are beginning at WSU aimed at settling this point.

6. References

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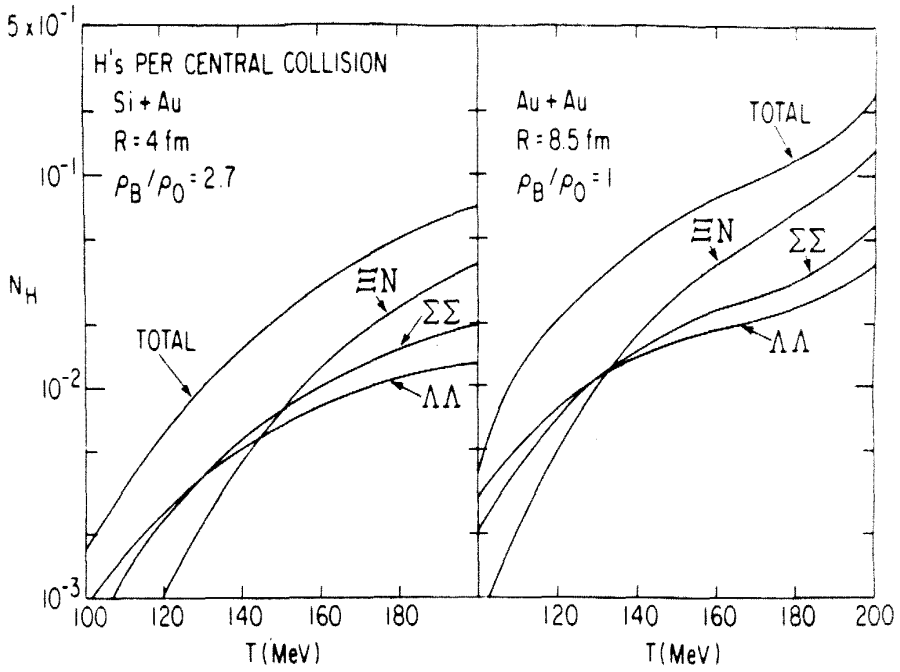

Fig. 1. Relative contribution of the ΛΛ, the ΣΣ and the ΞN fusion process to the H cross, section for Si+Au and Au+Au collisions assuming a simple coalescence model. The curves show the dependence on initial temperature (from [12]).

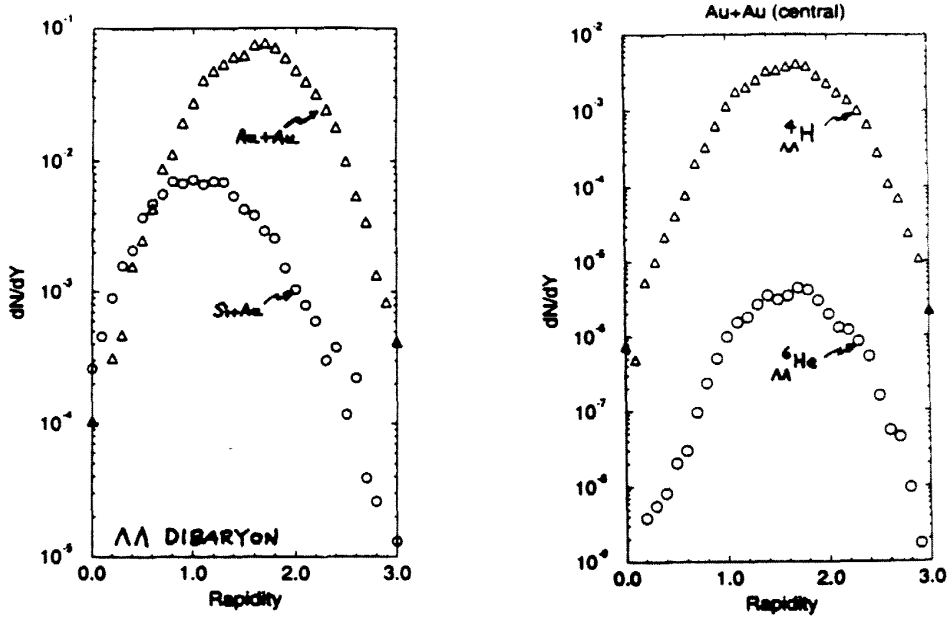

Fig. 2. ARC coalescence predictions for the rapidity distributions for a hypothetical ΛΛ-Dibaryon and a hypothetical ΛΛ hypernucleus in Si+Au and Au+Au collisions at the AGS (from [13]).

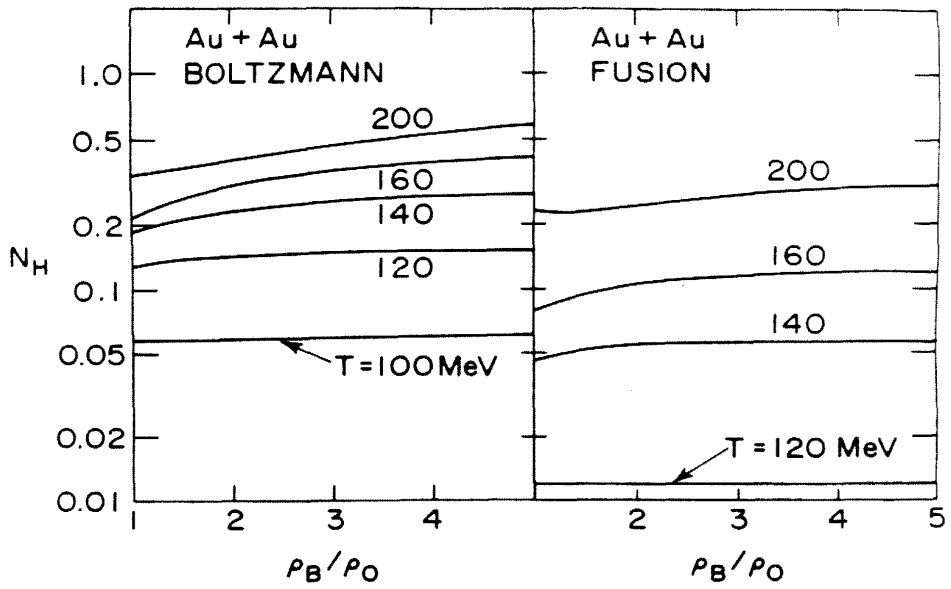

Fig. 3. The abundance of H's as calculated in the (a) Boltzmann particle approximation and (b) in the coalescence fusion model as a function of baryon density ρ_B for various incident temperatures in Au+Au collisions (from [12]).

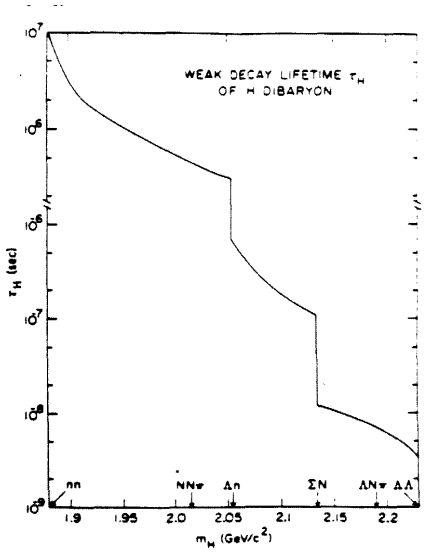

Fig. 4. The weak decay lifetime τ_H of the H-Dibaryon as a function of its mass (from [28]).

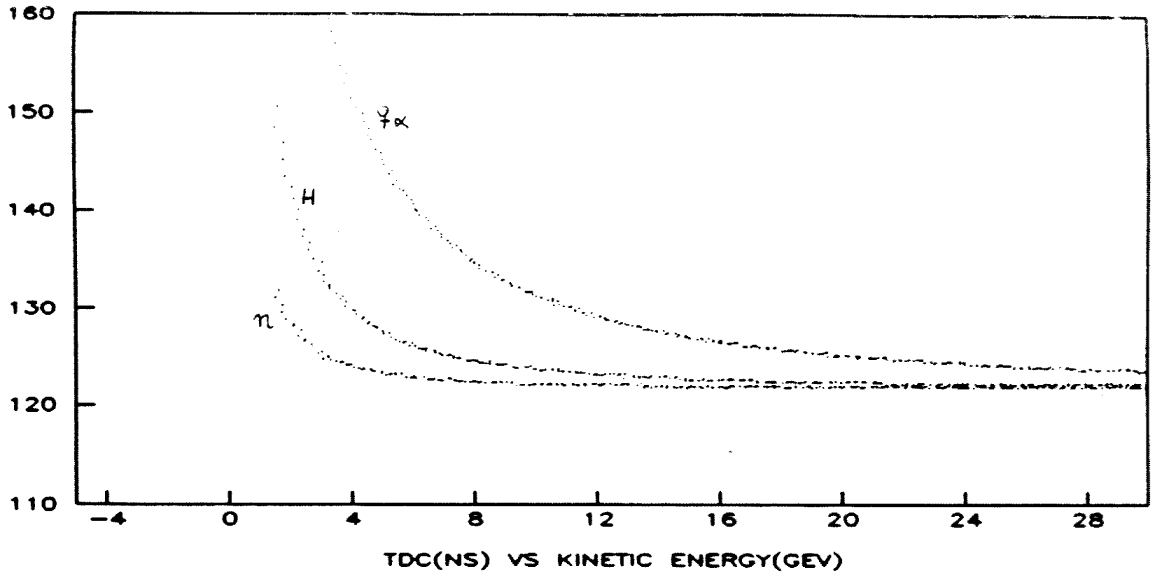

Fig. 5. Simulation of a TO vs. E_{kin} plot for neutrons, H-Dibaryons and q_α particles as seen by a calorimeter 36m downstream from the target. All lifetimes were assumed as long enough for the particle to reach the detector.

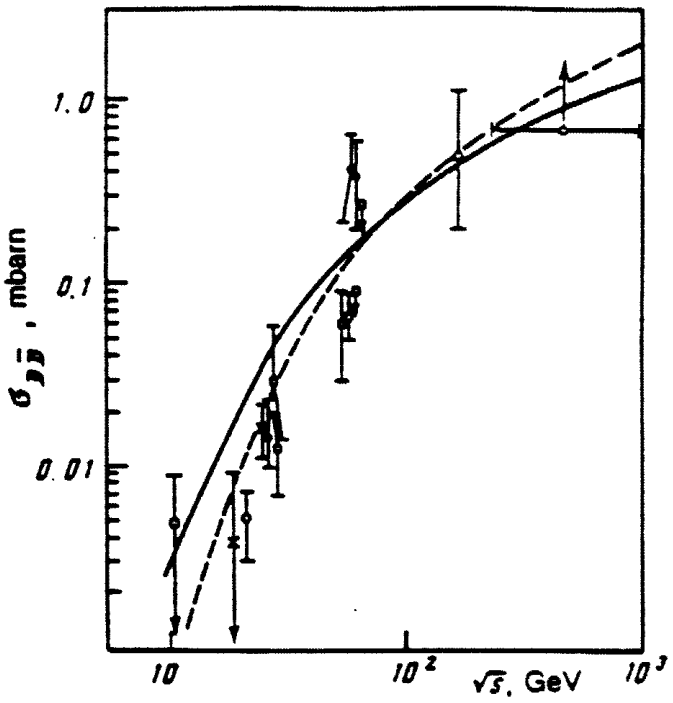

Fig. 6. Energy dependence of the total cross section for the production of DD pairs in pp collisions (from [29]).

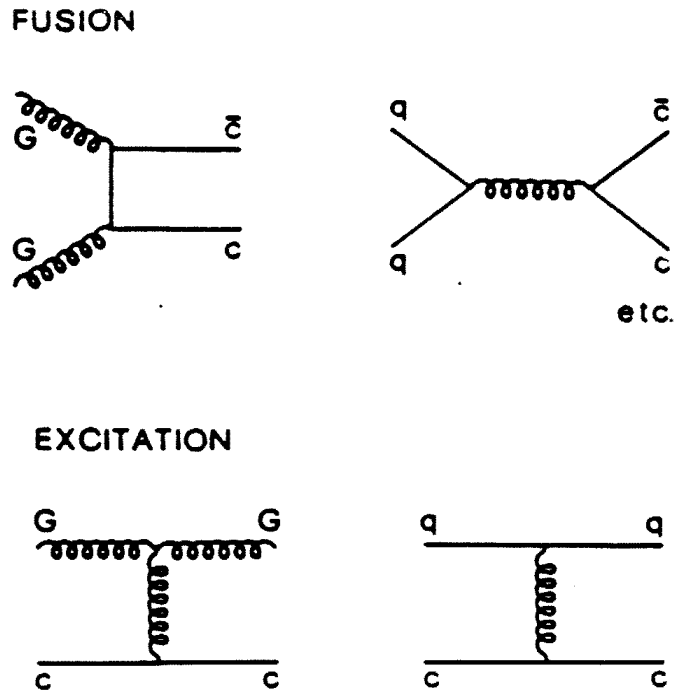

Fig. 7. Fusion and flavor excitation diagrams which contribute to cc production.

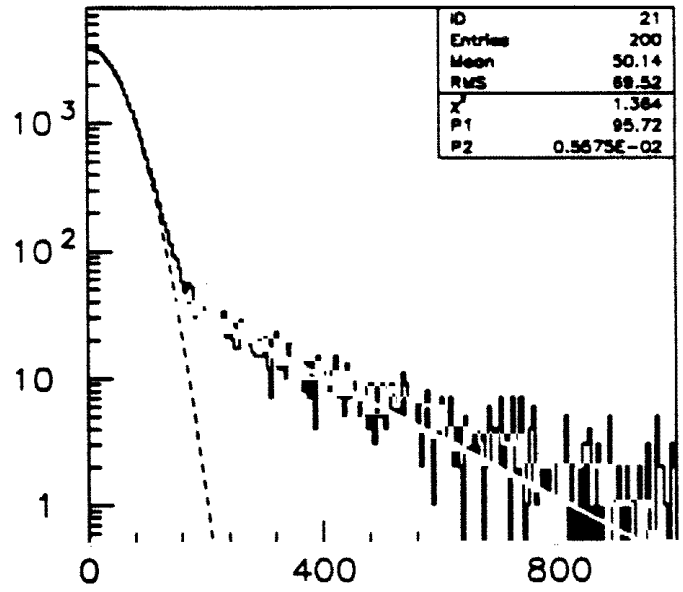

Fig. 8. Reconstruction of K vertex from 8000 central RHIC Au+Au events in STAR. A position resolution for the SVT was set to 20 micron. The reconstruction efficiency for K was assumed to be 100%.