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AN EVENT GENERATOR FOR THE FIRECRACKER MODEL AND THE RESCATTERING IN HIGH ENERGY pA and AA COLLISIONS LUCIAE VERSION 2.0

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Abstract: LUCIAE is a Monte Carlo program that, connected to FRITIOF, implements both the Firecracker Model (FCM), a possible mechanism for collective multi-gluon emission from the colour fields of interacting strings, as well as the reinteraction of the final state hadrons in relativistic pA and AA collisions. This paper includes a brief presentation of the dynamics of the model as well as a description of the program.

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PROGRAM SUMMARY

Title of Program: LUCIAE version 2

Program obtainable from: taian@thep.lu.se (internet)

Computer for which the programme is designed: DECstation, VAX, IBM and others with a FORTRAN 77 compiler

Computer: DECstation 3100; installation: Department of Theoretical Physics, University of Lund, Sweden

Program language used: FORTRAN 77

High speed storage required: $\approx$ 90k words

No. of bits in a word: 32

Peripherals used: terminal for input, terminal or printer for output

No. of lines in combined program and test deck: about 7000

Keywords: Monte Carlo, hadrons, nuclei, clusters, collective effects, gluon radiation, formation time, rescattering.

Nature of the physical problem: The experiments of relativistic pA and AA collisions reveal that high energy heavy-ion collisions have some features which can not be understood in a framework where pA and AA collisions correspond to simple superpositions of independent nucleon-nucleon collisions. The low P_t enhancement , highP_t enhancement, strangeness enhancement etc. clearly show that some collective effects are active in the relativistic pA and AA collisions. Formation of a QGP is often suggested to be a candidate for these collective effects. Could we understand those new features in the pA and AA collisions by conventional physics? The Monte-Carlo generator, LUCIAE is built in an attempt to answer this question.

Method of solution: When many strings or colour dipoles are formed in relativistic pA and AA collisions, it is natural to ask if there is some interaction between those dipoles so that they could emit gluons collectively using their common total energy density. The Firecracker Model is developed to study such a collective effect. Moreover, many hadrons are produced through hadronisation, which implies that they will interact with each other and with the surrounding cold spectator matter. The rescattering effect in the final state is also included in LUCIAE program.

Restriction of complexity of the problem: At very high energies ($\sqrt{s}$ in the TeV range), especially for collisions of massive nuclei, certain arrays need to be expanded to accommodate the large number of particles produced.

Typical running time: Depends on the type of collision and energy. Two examples running on Alpha Work Station:

$^{32}\mathrm{S} + {}^{32}S$	$p_{\mathrm{lab}} = 200$ A GeV$/c$:	$\sim$ 15 events/min
$^{32}\mathrm{S} + {}^{207}Pb$	$p_{\mathrm{lab}} = 200$ A GeV$/c$:	$\sim$ 4 events/min

LONG WRITE-UP

1 Introduction

One major reason to study heavy ion collisions at high energies from both a theoretical and experimental point of view is to search for traces of the predicted Quark-Gluon Plasma (QGP) and to investigate the properties of this new state of matter. The study is very important, not only because it provides a test of QCD on a new natural scale (an interacting system with high energy density), but also because it will improve our understanding of other fundamental concepts such as the nature of confinement and chiral symmetry breaking.

Many signals have been theoretically suggested as possible evidence for the formation of a QGP. So far, the energy density expected to be needed for the QGP formation ($\sim$ 1-2 GeV/fm^3 from QCD calculations on the lattice) should have been reached in the CERN 200 AGeV/c S-Pb central collisions. There is, however, no unambiguous ("smoking gun") signal in the experimental data at present. All the present predictions based on the formation of the QGP, although sometimes found in the data, can be explained also by non-QGP models. This means that it is not only necessary to consider the properties of the QGP itself but also to develop "conventional" models for possible and consistent dynamics, including different non-QGP collective effects. Such models should be used in order to provide possible background for the signals of QGP formation.

FRITIOF is a model for inelastic hadron-hadron scattering and it has been successful in describing many experimental data from the low energies at the ISR-regime all the way to the top SPS energies, [1][2]. This has been achieved by the introduction of a particular longitudinal momentum transfer scenario, gluon bremsstrahlung radiation (The Dipole Cascade Model, DCM, and the Soft Radiation Model, SRM, discussed in Section 2 — this is implemented by the use of ARIADNE, [3]) as well as hard parton scattering (Rutherford Parton Scattering, RPS — this is implemented by the PYTHIA routines, [4]). In FRITIOF, during the collision two hadrons are excited due to longitudinal momentum transfers and/or a RPS. The highly excited states will emit gluon bremsstrahlung according to the SRM and they are afterwards treated as Lund Strings and are allowed to decay into final state hadrons according to the Lund prescription as implemented by JETSET, [5] .

The FRITIOF model has been extended to also describe hadron-nucleus and nucleus-nucleus collisions by assuming that the reactions are superpositions of binary hadron-hadron collisions (the timescales involved in the nuclear states are much longer then those related to hadronic interactions) in which the geometry of the nucleus plays an important role because the nuclei should then behave as a "frozen" bag of nucleons. This picture is supported by the fact that the global features of the heavy ion collisions are satisfactorily explained by the collision geometry together with the independent hadron-hadron collisions.

On the other hand, in the experiments one finds that when both the baryon density and the energy density are large enough in high energy heavy ion collisions, some new features emerge. There is e.g. high P_t and low P_t enhancement in the particle spectra and there is also larger strangeness and anti-baryon production than the one obtained by a straightforward extrapolation from single hadron collisions. This means that there are some collective effects.

In the FRITIOF string language we find that there are generally many excited strings formed close by each other during a relativistic heavy-ion collision. In case these strings would behave like vortex lines in a color superconducting QCD vacuum then it is conceivable that they will interact ("ordinary" vortex lines in a type II superconductor are known to exhibit a repulsive interaction). In the FCM approach we will assume that there are groups of neighbouring strings which may form interacting quantum states so that both the emission of gluonic bremsstrahlung as well as the fragmentation properties can be affected by the large common energy density, [6].

In Ref [7] a model for interacting-string (a "Color Rope") fragmentation has been developed based on the fragmentation scheme of a single string in the Lund Model. Besides the "individual" string energy density (the string tension at rest $\kappa \simeq 1$ GeV/fm), there is also some interaction energy in the region of the overlapping strings (and this is further developed in Ref [8]). String interaction in the DPM model has also been discussed in, [9].

Many hadrons are produced through the fragmentation, which implies that they would interact with each other and with the surrounding cold spectator matter. The rescattering has been considered important in the relativistic heavy-ion collisions, [10].

In this paper we will consider a Monte Carlo implementation of the Firecracker Model (FCM). This model contains a simple collective mechanism to emit gluons from a system containing several interacting strings and the FCM is described in Section 3. We will also include the rescattering of the many hadrons which are formed in high energy pA and AA collisions. The rescattering dynamics is described in Section 4–5. The detailed description of the MC routines will finally be found in Section 6.

2 The Formation of Color Dipoles and their Radiation in the FRITIOF Model

In the FRITIOF model a hadron is assumed to behave like a massless relativistic string (MRS) corresponding to a confined color force field of a vortex line character embedded in a type II color superconducting vacuum. During the collision between two hadrons it is assumed that there are many momentum transfers and most of these are expected to be rather small and uncorrelated. It is further assumed that there is no net color exchange between the hadrons. The result of the many momentum transfers, q_j, is, based upon the properties of the classical motion of the MRS, assumed to be essentially additive, i.e.the string reacts as if it had been worked upon by a single (large) momentum transfer $Q = \sum q_j$ in one of its endpoints. In case one of the q_j's have a large transverse momentum component, it will correspond to a Rutherford parton-parton scattering (RPS) and the probability is treated according to the PYTHIA routines.

In this way there will be color separation in the model, i.e. there will for each hadron be a color $\bar{3}$ (a "diquark") continuing forward along the beam direction and a valence quark, a color 3, moving in the opposite direction due to the longitudinal momentum transfer (for the case of an occurring RPS there are further prescriptions, [2]). This will lead to bremsstrahlung of a dipole character. In an e^+e^--annihilation event there is also a dipole formed between the originally produced q (color

3) and $\bar{q}$ (color $\bar{3}$). The bremsstrahlung gluons are emitted according to the formula, [11]

$$d\sigma = \frac{C\alpha_s}{\pi}\frac{dk_\perp^2}{k_\perp^2}dy, \tag{1}$$

where $k_\perp$ and y are the transverse momentum and rapidity of the emitted gluon, C is a color factor ($C = 4/3$ for a $(q\bar{q})$-dipole) and α_s the strong coupling constant. Energy- momentum conservation provides the constraint

$$k_\perp \cosh(y) \leq \frac{M}{2} \tag{2}$$

with M the invariant mass of the emitting dipole. This relation is conveniently approximated by

$$k_\perp \lesssim e^{-|y|}M, \tag{3}$$

which means that the kinematically allowed phase space for the bremsstrahlung gluons corresponds to the interior of a triangular region in the $y - \ln(k_\perp^2)$ plane as shown in Fig.1a.

But contrary to an e^+e^--annihilation reaction the energy momentum in a hadronic reaction is not localised in a pointlike color charge but spread over some extended region. The dynamics of FRITIOF will produce (at least) two transversely extended fronts from each hadron containing the energy momentum as well as the color 3 q- and the $\bar{3}$ "diquark" charge. Any bremsstrahlung emission from an extended source will necessarily be influenced by this extension ("the form factor"). In the SRM it is advocated that in case the extension of the emitter is l and the wave length of the radiation is λ then only the part $(\lambda/l)^d$ of the energy momentum in the front (assuming that the front has d dimensions) is involved. From comparison to DIS data it has been found (note that in this case there is one presumably pointlike "kicked-out" quark and one extended "remainder" front) that $d \simeq 1$ (ie the "spectator" front behaves in a "string-like" scenarium) and $l \sim 1/\mu_0$ with $\mu_0 \simeq 0.6$ GeV in case we use $\lambda \simeq 1/k_\perp$ for the gluonic radiation. Therefore the available phase space represented by Eq.(3) in the rest frame of the string for the gluon emission is further restricted into the region

$$k_\perp \lesssim e^{-|y|}\frac{\mu}{k_\perp}M, \tag{4}$$

see Fig.1b. The parameter μ is not necessarily equal to the μ_0 in DIS but we have found that in case we have two fronts (as in FRITIOF) then a good description of high energy hadron-hadron data is provided by $l \to l/2$, ie $\mu \to 2\mu_0$. In the DCM (including the softening according to the SRM) the gluon emissions will occur so that the original dipole is divided into two new dipoles $\to$ three dipoles $\to$ four dipoles etc. Every time a new gluon is emitted and a dipole is divided. The building of dipoles corresponds in the single parton cascades (eg Webber-Marchesini) to "strong angular order", ie a coherence condition for the radiation.

For the hadron-nucleus and nucleus-nucleus collisions, the process has in the FRITIOF model been regarded as incoherent collisions on the nucleons. Thus a nucleon from the projectile interacts independently with the encountered target nucleons as it passes through the nucleus. The probability distribution for the number of inelastic collisions ν is taken from geometric calculations. Each of the sub-collisions is treated in the same way as an ordinary hadron-hadron collision, although the momentum transfers will again be additive and every encounter will make the projectile more excited. If it interacts with ν nucleons in the target, $\nu + 1$ excited string states will be formed as a result. These string states will then independently emit associated bremsstrahlung radiation based on the Soft Radiation Model described above.

3 The Physics behind the FCM

3.1 Gluon Emission from The Colour Field of a Multi-String State in accordance with the FCM

In accordance with the FRITIOF scenarium many strings are formed inside a small space-time volume and it is conceivable that these objects cannot be treated as independent.

We have already mentioned the possible relationship between the vortex lines in a type II superconductor and the string-like color force fields described by the MRS in the Lund Model. In an electro-magnetic superconductor type II there are three state regions when the magnetic field $\mathcal{H}$ is used as the order parameter. When the field is below a certain number, $\mathcal{H}_1$, the Meissner effect works, but in a region $\mathcal{H}_1 \leq \mathcal{H} \leq \mathcal{H}_2$ the quantized vortex lines start to penetrate the superconducting state and exhibit a repulsive interaction. Above $\mathcal{H}_2$ the field is so strong that the whole region "melts" into a state of the same character as the break-down of a superconductor type I, ie a (space-)extended "bag" or "flux-tube" region. This is the usual intuitive picture of the QGP.

The FCM is assumed to work inside the intermediate region (with the energy density as the order parameter). This means that the strings at this stage interact but still keep some individuality. We note that the Eq (4) contains the factor μM which effectively corresponds to an energy density over the region $1/\mu$. The basic assumption in the FCM is that *in the very early stage of the collisions when several (n) excited strings (with energy momenta (P_{+j}, P_{-j}) are close by it may be possible for them to emit gluons using their common total energy density $\mu \sum P_{\pm j}$* .

In order to estimate the effect we may for simplicity assume that the (n) strings are at rest relative to each other with the same masses $W_j = W$. This means that *each string may be able to take energy from the common pool nW.* Thus one may in principle be able to emit n gluons, each with a transverse momentum limited by $\sqrt{\mu n W}$!

3.2 The partitioning into Interacting Quantum States

We will next introduce a way to determine the interacting multi-string states. The partitioning can be done in different ways but it is evident that only strings which are "close by" each other (in some way to be defined) should be able to interact and form a common energy pool.

In a hadron nucleus collission we assume that all the participant nucleons from the target form a single interacting system after the collission. The impinging hadron is assumed to move along a straight line path and to interact with the nucleons along the path in accordance with an overlap function mechanism in the impact parameter. Therefore we assume that all the participating nucleons (of the target) are close to each other transversely. In a nucleus-nucleus collission, however, the projectile nucleons have different impact parameters with respect to the target nucleus. The strings excited in the projectile and in the target have in general a large relative longitudinal motion and we will assume that they form independent interacting sets, to be called "clusters", see Fig.2.

We will then partition the final state strings from each nucleus into groups with a small transverse motion with respect to each other. In order to do that consistently we apply the algorithm which was introduced in Ref [12]. There are three main steps in this momentum space clustering scheme:

1. For every pair of projectile or nucleons, k and l, the distance variable d_{kl} is defined by means of the pseudorapidities η, azimuthal angles ϕ and the transverse momenta p_t:

$$d_{kl} = min(p_{tk}, p_{tl})\sqrt{(\eta_k - \eta_l)^2 + (\phi_k - \phi_l)^2} \tag{5}$$

   Find the pair with the minimum distance d_{kl} !

2. If this minimum d_{kl} is smaller than a value d_{cut} we combine k and l into a single "pseudoparticle" with a four-momentum p_{kl} given by

$$p_{kl} = p_k + p_l \tag{6}$$

3. Repeat the procedure for all nucleons and pseudoparticles until all remaining pairs have a distance larger than d_{cut}. The remaining objects now define the clusters.

It is possible to introduce a clustering procedure also in the corresponding (coordinate) impact parameter space. The resulting clusters will (although not event by event) be very similar to the ones obtained above. As it is more in the spirit of the model to consider energy momentum space (and also because for simulation reasons it is easier to implement it) we chose to use the momentum space clustering.

In case there is a Rutherford parton interaction on one of the strings we assume that the coherence between that and the rest of the cluster is lost. Such a string is not taken into account in connection with the "collective" gluon emission in the FCM (although we test if the Rutherford $k_{\perp R}$ is larger than the possible bremsstrahlung $k_\perp$ in order to fulfill the requirements of perturbation theory, ie a relevant perturbative contribution is always governed by the largest momentum transfer).

We now assume that there is inside a small (Lorentz contracted) space time region a set of n excited FRITIOF strings formed during the high energy nuclear interaction in accordance with the clustering assumptions. We neglect their transverse motion and we parametrise their longitudinal motion in terms of lightcone coordinates (P_{+j}, P_{-j}) along the beam direction. The total energy momentum of the cluster is

$$P_{\pm tot} = \sum_{j=1}^{n} P_{\pm j} \tag{7}$$

We next assume that the set forms a quantum state of n interacting objects. The repulsive interaction may be small but if it is there it means that the strings will be aligned in such a way that they all of them may use the common total energy density $\mu P_{\pm tot}$ in the emission of bremsstrahlung gluons. We further assume that energy-momentum in connection with the emissions is "locally" conserved. Therefore a gluon emitted according to the FCM can be related to a particular string only if (in the corresponding string cms) the Eq (2) is fulfilled.

In case we produce a gluon in accordance with this procedure, using the total energy density, then there are several possibilities to relate the gluon to anyone of the strings. We have considered three such schemes

A We emit n gluons from a cluster with n strings. Then we stochastically pick a gluon and a string out of the set and try to match them. In case the gluon fulfils Eq (2) it is "accepted" and the emission allowed, otherwise we drop the gluon and consider this string not to have a firecracker gluon. Then the procedure is repeated for the next gluon and the next string.

B As A, but we order the n gluons by their invariant $k_\perp$ and also the original string set from the largest mass downwards and then try to match the j-th gluon to the j-th string (j=1, 2, $\cdots, n$).

C In this case we emit a gluon without any ordering of the original set and try to find a string in the set for which Eq (2) is fulfilled. If there are several then we take the largest mass string and emit the gluon and remove the string from the set. If there is no string available that "fits" to the gluon then we remove the largest mass string. Next we emit a second gluon and repeat the procedure.

There is in our experience no large differences among the three procedures and we have therefore only kept the possibility A as an option in the Monte Carlo. The main idea is to assume that just as for a Rutherford scattering a hard FCM gluon breaks the coherence in the interaction set and therefore the corresponding string state no longer contributes to the FCM mechanism.

The result is that the original set of strings is partitioned into those endowed with a collective FCM gluon and those for which the test failed and therefore they are still "longitudinal strings". These latter strings can then also emit gluon bremsstrahlung but only according to the "individual" application of the SRM. In all cases the dipole cascades are continued downwards to a suitable cutoff and afterwards the strings are fragmented according to the Lund prescriptions. In that case there is no sensitivity to the gluon emission cutoff, ie *the procedure is infrared stable.*

4 Initiation of The Rescattering Transport Process

4.1 The Formation Time Concept

It is evidently not reasonable to expect that there will be no (re)interaction when there is a large density of final state hadrons produced in a dense string surrounding as conceived in the FRITIOF scenarium. In this and the next section we will consider these reinteractions and we will start with the notion of "formation time".

In the LUND fragmentation model the probability distribution in invariant time, τ, of the $q\bar{q}$ breakup vertices (which is only partly what one would like to call "the formation time of a hadron") has been given in terms of $\Gamma = (\kappa\tau)^2$ as [13]

$$P(\Gamma)d\Gamma \propto \Gamma^a exp(-b\Gamma)d\Gamma \tag{8}$$

with its mean value ,

$$< \Gamma >= \frac{a+1}{b}. \tag{9}$$

Here a and b are the fragmentation parameters and κ is the energy density of the string. Using the parametrical values obtained from experimental fits the mean formation time $< \tau >$ should be around 1 fm. For simplicity, we will use this value of $< \tau >$ as a parameter called *the formation time of all the hadrons produced from a string.* In a moving frame the formation time of a hadron with mass m and energy E is $t =< \tau > E/m$.

4.2 The Initiation in Space-Time

We will assume that from the formation time and onwards a particular final state hadron will be moving "outwards" and therefore be available for rescattering and so will the the "spectators" (ie those nucleons which did not participate in the high energy encounter). We also make use of classical trajectories for each one of the produced hadrons assuming that the produced particles are initially randomly placed at the formation time in space inside the (classical) overlap region of the participant and the nucleus. The "spectator" nucleons are likewise randomly distributed inside the non-interacting region and provided with a thermal motion in accordance with a Boltzman distribution. We require as always that that there is a minimum distance between such spectators ("the hard intranuclear core potential") of 0.5 fm.

4.3 The Initiation in Momentum Space

The produced particles from the fragmentation have already had their four-momentum calculated according to the LUND Fragmentation Model. For the projectile spectator nucleons, it is reasonable to assume that they share the remaining longitudinal momentum of the projectile, ie the one not used up to produce hadrons. The transverse momentum of the spectators are sampled according to the two dimensional Gaussian distribution

$$f(p_t)dp_t = Cp_t \exp[-\frac{p_t^2}{< p_t^2 >}]dp_t. \tag{10}$$

Here $\sqrt{< p_t^2 >}$ is taken to be 200 MeV. The transverse momentum of the last projectile spectator nucleon should be decided by transverse momentum conservation so that the energy-momentum conservation is guaranteed.

4.4 The Classical Motion of The Particles and The Collision Times

The hadrons are treated as classical, point-like particles, which move along straight-line trajectories between two consecutive collisions

$$\vec{r_i} = \vec{R_i} + \vec{\beta_i}(t - T), \tag{11}$$

where $\vec{R_i}$ and T is the four-coordinate of the i-th particle at the time of the last collision.

In order to perform the collisions in a consistent way it is necessary to introduce a time ordering procedure. We have chosen to calculate the time between the last and the next collision for all pairs of particles and then chosen the minimal time. Two particles will collide if their distance approaches d_{min} with

$$d_{min} \leq \sqrt{\frac{\sigma_{tot}}{\pi}}, \tag{12}$$

where σ_{tot} is the total cross section in fm^2. Since the minimum distance depends on the reference frame it is necessary to view this problem in an inertia frame, where the distance of the closest approach will be perpendicular to the momentum of both particles, [14]. We have chosen the cms frame of the two colliding particles. If the particles i and j are chosen as an example, their equations of motion are

$$\vec{r}_i^* = \vec{R}_i^* + \vec{\beta}_i^*(t^* - T_i^*) \quad \text{and} \quad \vec{r}_j^* = \vec{R}_j^* + \vec{\beta}_j^*(t^* - T_j^*). \tag{13}$$

Thus one may calculate the relative distance squared between the particle i and j, $d^2(t^*)$. The minimum distance, d^2_{min1}, in the orbits and also the collision time is obtained from

$$\frac{\partial(d^2(t^*))}{\partial t^*} = 0 \quad \text{ie} \quad t_{ij}^* = \frac{[\Delta\vec{R}^* \cdot \Delta\vec{\beta}^* + \Delta\vec{\beta}^* \cdot (\vec{\beta}_j^* T_j^* - \vec{\beta}_i^* T_i^*)]}{(\Delta\vec{\beta}^*)^2} \tag{14}$$

$$\Delta\vec{R}^* = \vec{R}_j^* - \vec{R}_i^* \quad \text{and} \quad \Delta\vec{\beta}^* = \vec{\beta}_j^* - \vec{\beta}_i^*. \tag{15}$$

The d^2_{min1} must satisfy the Eq (12) and as the collisions must be causal the collision time must fulfil

$$t_{ij}^* \geq Max(T_i^*, T_j^*). \tag{16}$$

After the collision times of all pairs have been calculated in their own cms one has to transfer them back to the lab system.

5 The Treatment of the Particle-Particle Collisions

5.1 The Elastic Scatterings

A particle-particle collision is always performed in the joint cms, for both elastic and inelastic scatterings. If the total and the elastic cross section satisfies

$$\frac{\sigma_{el}}{\sigma_{tot}} \geq \xi \tag{17}$$

where ξ is a random number, then the particles will be elastically scattered or else the collision will be considered as inelastic, cf the next subsection. The distribution of the momentum transfer, t, will for elastic scattering be taken as, [15]

$$\frac{d\sigma}{dt} \sim \exp(Bt), \tag{18}$$

$$B = \frac{\epsilon^6}{1+\epsilon^6}A, \tag{19}$$

$$\epsilon = 3.65(\sqrt{s} - m_i - m_j), \tag{20}$$

$$A = Min[10.3, (1.12 < p_t >)^{-2}], \tag{21}$$

where $< p_t >$ is the average transverse momentum of the rescattered particles. Thus t is calculated by means of the random number ξ as

$$t = \frac{1}{B} \ln[\xi + (1 - \xi) \exp{(Bt_0)}] \quad \text{with} \quad t_0 = -4(p_i^*)^2. \tag{22}$$

The polar angle of the scattering is then related to t by

$$t = -2(p_i^*)^2(1 - \cos(\theta^*)). \tag{23}$$

and the azimuthal angle will be isotropically distributed.

5.2 The Inelastic Collisions

As it is impossible to include all inelastic channels in the program we have chosen to consider only those reactions which we have found to give noticeable effects in the final state spectra. The following reactions are included in LUCIAE2.0:

- 1) $\pi + \pi \rightarrow \overline{K}+K$
- 2) $\pi + N \rightarrow \Delta+\pi$
- 3) $\pi + N \rightarrow \rho+N$
- 4) $N + N \rightarrow \Delta+N$
- 5) $\pi + N \rightarrow K + Y$
- 6) $\pi + \overline{N} \rightarrow \overline{K}+\overline{Y}$
- 7) $\overline{K} + N \rightarrow \pi + Y$
- 8) $K + \overline{N} \rightarrow \pi + \overline{Y}$
- 9) $K + \overline{N} \rightarrow \overline{K} + \overline{\Xi}$
- 10) $\overline{K} + N \rightarrow K + \Xi$

where the hyperons are Y=Λ or Σ. Another possible reaction reaction, $N + N \rightarrow N + Y + K$, plays almost no role due to the smallness of the available phase space and the ensuing rate, [16].

The relative probabilities for the different channels in eg (πN)-scattering, (the reactions 2,3 and 5 above) is used to determine the outcome of the inelastic encounter. As the reactions introduced above do not make up the full inelastic cross section, the remainder is again treated as elastic encounters.

We will for simplicity assume that the total, elastic and inelastic cross sections for NN, πN, KN and $\pi\pi$ interactions are constants and we will use the following values for them: $\sigma_{tot}^{NN} = 40$ mb, $\sigma_{tot}^{\pi N} = 25$ mb, $\sigma_{tot}^{KN} = 35$ mb and $\sigma_{tot}^{\pi\pi} = 10$mb. The ratio of the inelastic to the total cross section will be taken as $0.75 \sim 0.85$. Further the cross section for $\pi\pi \rightarrow \overline{K}K$ is conventionally taken to be 2.0 mb.

An isospin averaged formula parametrised in Ref [16] is used for the cross section of the reaction $\pi + N \rightarrow K + Y$. The cross section for the $\overline{K}N$ induced strangeness exchange reactions is assumed to be equal to ten times the corresponding cross section for the πN induced strangeness production reactions, [16]. Finally the cross section for the reactions $\pi\overline{N}$ and $K\overline{N}$ are assumed to be equal to the corresponding cross sections for the reactions πN and $\overline{K}N$ interactions, respectively.

The cross sections of inelastic reactions given by the isospin averaged parameterization formulas of Ref [16] for $\pi N \rightarrow K + Y$ decrease exponentially with cms energy of the two colliding particles. On the other hand we know that the total inelastic cross sections of πN are approximately energy-independent, which means that more inelastic reactions would take place like $\pi^- p \rightarrow K^{*0} + \Lambda \rightarrow K + \pi + \Lambda$ and $\pi^- p \rightarrow K^{*0} + \Sigma^0 \rightarrow K + \pi + \Sigma^0$ etc., when cms energy of the two colliding particles is increasing. In some sense the reactions we listed above should be looked upon as "representative channels" of certain type of reaction. Therefore, instead of applying the energy-dependent inelastic cross section, we could alternatively give a constant "effective cross section" to the reactions $\pi N \rightarrow K + Y$.

We always assume that the highest isospin state contributes to the inelastic cross sections in order to calculate the relative cross sections for the different isospin channels. As an example, for the reaction $\pi + N \rightarrow \Delta + \pi$ we assume that the isospin $I = 3/2$ state is dominant. By giving a relative cross section to each inelastic channel the isospin conservation is guaranteed in the rescattering process.

All the inelastic channels included in LUCIAE2.0 can be found in Appendix A together with their relative cross sections.

As usual, two body final state, i.e. the energy and momentum of the scattered particles of the inelastic reactions above can be calculated from two-body kinematics, [17], in the cms of the colliding particles, i.e.

$$E_i^* = \frac{s - m_j^2 + m_i^2}{2\sqrt{s}}, \tag{24}$$

$$|\vec{p_i^*}| = \frac{\sqrt{(s-(m_i+m_j)^2)(s-(m_i-m_j)^2)}}{2\sqrt{s}}. \tag{25}$$

The orientation of the three momentum is isotropically sampled in 4π for $\pi\pi$ and NN collisions as suggested in Ref [15], but for the rescattering between a meson and a baryon we assume that the final state baryon moves along the direction of the incoming baryon in the cms of the colliding particles.

We will finally assume that all the unstable particles produced through the rescattering processes will survive until the end of the heavy-ion collision process.

6 The Description of the Program

LUCIAE2.0 is a subroutine package for simulating collective gluon emission in the Firecracker Model as well as the rescattering of the produced particles from FRITIOF in a nuclear environment. The program is written in FORTRAN 77. It should be used together with FRITIOF7.02, [18], JETSET7.3, [5], PYTHIA 5.5, [4] and ARIADNE4.02, [3]. A user should read paper [18] first before using LUCIAE2.0 if he is not familiar with using FRITIOF7.02. To run with LUCIAE2.0, FRITIOF7.02 and ARIADNE4.02 have been somewhat modified and are called FRITIOF7.02R and ARIADNE4.02R, respectively.

One important thing that a user has to keep in mind is that the dimension size of the common block COMMON/LUJETS/ (KSZJ) and COMMON/FRPARAI (KSZ1) have been extended. Now KSZJ=20000 and KSZ1=30. Those who have used FRITIOF7.02 before will find it is very easy to use FRITIOF7.02R which is linked to LUCIAE2.0 since the input and output structure of the two programs are completely the same. One simply starts with the subroutine FREVENT and ends with final state particles (after the firecracker gluon emission and rescattering) recorded in event record LUJETS.

The rescattering part of LUCIAE2.0 is quite time consuming. The time consumption increases rapidly with the mass of the nuclei and the collision energy. S+Pb collision at a lab frame energy of 200 AGeV/c, for example, the time consumption in this part of the program increases compared to "plain" FRITIOF by a factor of 3. If a user is not interested in the distributions highly affected by the rescattering process, like the distributions related to strangeness production etc he might like to run LUCIAE without the rescattering. This is done by setting KFR(21)=0.

6.1 User interface

This section contains the most essential information a user should know about the program, namely the common block FRPARA1 and LUCIDAT2 for input parameters and switch controls. The input parameters are provided with sensible default values. Several options are also included to make the program more accessible to user.

- PARAMETER (KSZ1=30)
  COMMON/FRPARA1/KFR(KSZ1), VFR(KSZ1)

  Note: KFR(1-14) and VFR(1-16) are used in FRITIOF7.02. We still list them here since some small change has been made.

  KFR(1) (D=1) Fragmentation

  =0 Off.

  =1 On.

  KFR(2) (D=1) Multiple gluon emission (dipole radiation)

  =0 Off.

  =1 On.

KFR(3) (D=0) Event selection for collisions with a nucleus

- **=0** Generate minimum bias events (all interactions recorded).
- **=1** Generate only events with all projectile nucleons participated.
- **=2** Generate only events with impact parameter between b_{min}=VFR(1) and b_{max}=VFR(2).
- **=3** Apply both requirements in 1 and 2.

KFR(4) (D=1) Fermi motion in nuclei

- **=0** Neglected.
- **=1** Included.

KFR(5) (D=0) Nucleon-nucleon overlap function

- **=0** Eikonal.
- **=1** Gaussian.
- **=2** Gray disc.

KFR(6) (D=2) Target Nucleus deformation

- **=0** No deformation.
- **=1** Deformed target nucleus.
- **=2** Apply deformation only if the target atomic number $A \geq 80$.

KFR(7) (D=1) Rutherford parton scattering processes

- **=0** Off.
- **=1** On. Here only the hardest RPS is used in FRITIOF.
- **=2** On. The full multiple hard scattering scenario of PYTHIA is used.

KFR(8) (D=1) Hard gluons cause a corner (soft gluon kink) on the string

- **=0** No kink is formed.
- **=1** Gluon kink is formed.

KFR(9) (D=1) 'Drowning' of Rutherford parton scattering

- **=0** Off. Accept all RPS events.
- **=-1** On. Throw away the drowned RPS event completely and replace it by a purely soft event.
- **=1** As in -1, but the transverse momentum transfer of the soft collision is superimposed by the q_T of the drowned RPS.

KFR(10) (D=1) SRM parameters in RPS events: $\mu_1 = \mu_0/r$, $\mu_2 = \mu_0/(1-r)$

- **=0** μ remains the same as in a soft event: $\mu_1 = \mu_2 = \mu_0$.
- **=1** r = VFR(16).
- **=2** r takes a uniform distribution in (0,1).

KFR(11) (D=4) Write out of a message when the arguments in FREVENT is changed.

- **=-1** Write it out every time the change occurs.
- **=n ($n \geq 0$)** The write out is limited to n times.

KFR(12) (D=2) Set up of the dipole cascade and string fragmentation parameters.

- **=0** No set up. The default values are used.
- **=1** Set to the values optimised by OPAL collaboration, [19]: PARA(1)=0.20, PARA(3)=1.0, PARJ(21)=0.37, PARJ(41)=0.18, PARJ(42)=0.34.

=2 Set to the values optimised by DELPHI collaboration: PARA(1)=0.22, PARA(3)=0.6, PARJ(21)=0.405, PARJ(41)=0.23, PARJ(42)=0.34.

KFR(13) (D=0) Compresses the event record to save space in LUJETS. This switch is particularly needed for heavy ion collisions at high energy where LUJETS must be compressed before it gets overfilled.

=0 Do not compress LUJETS.

=1-3 LUEDIT(KFR(13)) is called and LUJETS is compressed. Specifically, for KFR(13)=1 fragmented jets and decayed particles are removed, for KFR(13)=2 neutrinos and unknown particles are also removed, and for KFR(13)=3 neutral particles are further excluded.

=4 A dummy subroutine FREDITD() is provided as an interface in which a user may write his own special purpose codes to edit and compress LUJETS.

KFR(14) (D=0) Checked for charge and energy-momentum conservation

=1 The outcome of each event will be checked.

=0 No checked.

KFR(15) (D=1) FIRECRACKER model

=1 On.

=0 Off.

KFR(16) (D=1) Firecracker gluon

=1 Accept firecracker gluons which are kinematically allowed.

=0 Reject all firecracker gluons. It is equivalent to KFR(15)=0.

KFR(17) (D=1) The 'drowning' of firecracker gluons by bremsstrahlung radiation.

=1 No drowning.

=0 Drowning.

KFR(18) (D=1) Size of firecracker cluster

=1 The size of firecracker cluster = VFR(17)$< P_t >$, with $< P_t >$ being average transverse momentum of nucleons in the cluster.

=0 size of firecracker cluster =VFR(18).

KFR(19) (D=0) Form of output ,only used when KFR(21)=0

=1 Output in event record includes decayed strings.

=0 Decayed strings have been taken away in output.

KFR(20) (D=1) The energy dependence of the cross section of an inelastic scattering

=1 Constant cross section.

=0 Energy-dependent cross section.

KFR(21) (D=1) Rescattering

=1 On.

=0 Off.

KFR(22) (D=1) Rescattering channel

=1 All channels are included.

=0 Only the reactions with the yield of the resonants Δ and ρ are included.

KFR(23) (D=0) Checked for charge and energy-momentum conservation after rescattering

=1 The outcome of each event will be checked.

=0 No checked.

VFR(1) (D=0.0 fm) Minimum impact parameter for options KFR(3)=2 or 3.

VFR(2) (D=0.2 fm) Maximum impact parameter for options KFR(3)=2 or 3.

VFR(3) (D=0.8 fm) The minimum allowable distance R_{min} between nucleons in a nucleus.

VFR(4-5) (D=0.2, 0.1) Dipole and quadrupole deformation coefficients for deformed target nucleus.

VFR(6) (D=0.01 GeV$^2/c^2$) The $< Q_T^2 >$ for the Gaussian distribution of soft transverse momentum transfer.

VFR(7) (D=0.20 GeV$^2/c^2$) The $< Q_{2T}^2 >$ for the Gaussian distribution of primordial transverse momenta on the string ends.

VFR(8) (D=0.75 GeV) Soft radiation coherence parameter μ_0 for projectile hadron or nucleon.

VFR(9) (D=0.75 GeV) Soft radiation coherence parameter μ_0 for target hadron or nucleon.

VFR(10-11) (D=0.0, 0.0 mb) Projectile-target nucleon total and elastic cross sections, respectively. By default, they are taken from the parameterization of Block and Cahn, [20] (MSTP(31)=5 in PYTHIA). The meson-nucleon cross sections are obtained simply by scaling down the Block-Cahn fit. The scale factor is $(2/3-a/\sqrt{s})$, where $a = 1.13$ GeV for pions and $a = 3.27$ GeV for kaons are chosen to reproduce the low energy experimental data. For all the other baryons, it is treated as a pion if it is a meson and it is treated as a proton if it is a baryon. User may override the default by setting VFR(17-18) to positive values. However, the user assigned cross sections will only affect the N-N interaction probability in nucleus collisions. The probability for Rutherford parton scattering is not affected.

VFR(12) (D=1.0 GeV/c) The q_{Tmin} for Rutherford parton scattering.

VFR(13-15) (D=1/6, 1/3, 1/2) The probabilities for assigning various spins and flavours to the diquark end of the string. For example in a proton, VFR(13-15) are the probabilities of finding a ud diquark of spin 1, a uu diquark of spin 1, and a ud diquark of spin 0, respectively.

VFR(16) (D=0.5) The fraction r in option KFR(10)=1.

VFR(17) (D=0.75) The size of firecracker cluster with respect to the average transverse momentum of nucleons in the cluster. See also KFR(18).

VFR(18) (D=0.35GeV/c) The size of firecracker cluster when KFR(18)=0.

VFR(19) (D=6.5GeV) Minimal CMS energy for starting FIRECRACKER model.

VFR(20) (D=0.7mb) Cross section for $\pi N \to K + Y$ when KFR(20)=1.

VFR(21) (D=7.0mb) Cross section for $\pi + N \to \Delta + \pi$ when KFR(20)=1.

VFR(22) (D=2.0mb) Cross section for $\pi + N \to \rho + N$ when KFR(20)=1.

VFR(23) (D=17.0mb) Cross section for $N + N \to \Delta + N$ when KFR(20)=1.

- COMMON/LUCIDAT2/KFMAXT,PARAM(20),WEIGH(150)

KFMAXT (D=22) The maximum number of particle species included in rescattering.

PARAM(1) (D=40.0mb) The total cross-section of reaction $N - N$.

PARAM(2) (D=25.0mb) The total cross-section of reaction $\pi - N$.

PARAM(3) (D=35.0mb) The total cross-section of reaction $K - N$.

PARAM(4) (D=10.0mb) The total cross-section of reaction $\pi - \pi$.

PARAM(5) (D=2.0mb) The cross section of $\pi + \pi \to \overline{K}K$.

PARAM(6) (D=0.85) The ratio of inelastic cross-section to total cross-section.

PARAM(7) (D=1.5fm) The formation time of a hadron at its rest-frame.

PARAM(8) (D=0.02fm) The minimal step of time elapsing.

PARAM(9) (D=0.1) The accuracy of four-momentum conservation when sampling spectator nucleons.

PARAM(10) (D=1.0) The size of effective rescattering region is PARAM(10)R_t with R_t being the radius of target.

PARAM(11) (D=0.16/fm^3) The nucleon density of nucleus.

PARAM(12) (D=0.04 GeV$^2/c^2$) $< P_t^2 >$ for the Gaussian distribution of spectator nucleons.

WEIGH(1)-WEIGH(150) The relative cross sections of the inelastic reactions, see Appendix A.

6.2 Other common blocks

The following common blocks are used for transmitting data internally. While they can be accessed to read out information, they should never be used to input data.

- COMMON/FCRSOUT/MCL(10),INEL(40),NST(2,KSZ4),ACL(2,KSZ4)

MCL(1): The number of cluster from projectile.

MCL(2): The number of cluster from target.

MCL(3): The number of accepted firecracker gluons.

MCL(4): The number of the initial collision pairs of rescattering.

INEL(I): The total number that I-th inelastic channel takes place in aggregate. Order corresponds to the list in Appendix A.

NST(L,J): The number of strings in J-th cluster. L=1,2 - index to label projectile (L=1) and target (L=2).

ACL(L,J): The invariant mass of J-th cluster. Index L has the same meaning as in NST(L,J) .

- PARAMETER (mcludi=20000)
  common/wz/c17(mcludi,3),ishp(mcludi),tp(mcludi)

c17(i,j): The coordinates of i-th particle, j=1,2,3 stands for x,y,z, respectively. The origin of the coordinates are at the center of target with z along beam direction.

tp(i): The time of i-th particle.

ishp(i): The status of i-th particle. =1 inside the rescattering region and =0 outside.

Except information which is stored in the particle list (COMMON/JETSETS/), other important information for proceeding rescattering is stored in collision list. The variables relevant to the collision list are:

lc(i,j): i indicates the order number in the collision list,

j=1 and 2 give the order number of the colliding particles in the particle list, respectively,
j=3 and 4 give the flavor code of the scattered particles, respectively,
j=5 indicates which kind of inelastic scattering is selected.

tc(i): collision time.

tw(i): The ratio of the reaction cross section of the selected inelastic process to the total cross section.

6.3 The main subroutine

Following subroutines build the main framework of the program. It might be worthwhile to know.

- SUBROUTINE FRCLUST
  to cluster the wounded nucleons by their relative transverse momenta.
- SUBROUTINE FRARCLU
  to emit gluons from the FIRECRACKER Model.
- SUBROUTINE FRCRGLU
  to assign the firecracker gluons to strings.
- SUBROUTINE FRINGES(KT,PT,VT,KT0,PT0,NB,N0)
  to emit bremsstrahlung gluons from the strings without RPS.
- SUBROUTINE FRINGEH
  to emit bremsstrahlung gluons from the strings with RPS.
- SUBROUTINE FRRESEXE
  to administrate the rescattering of final particles.
- SUBROUTINE even_init(lc,tc,tw,i)
  to proceed the initiation of the rescattering transport process.

- SUBROUTINE rescat(i,ij)
  to proceed rescattering.
- SUBROUTINE ctlcre(lc,tc,tw,n)
  to create initial collision list.
- SUBROUTINE his(time,lc,tc,tw,istop)
  to perform classical Newton motion.
- SUBROUTINE coinel(l,l1,ss,b,pi,pj,icp,pii,pjj,lc,tc,tw,winel,ik3,ik4)
  to check if an inelastic reaction could take place. Go head if one channel is chosen.
- SUBROUTINE coelas(l,l1,ss,pi,pj)
  to perform elastic scattering.
- SUBROUTINE updatl(l,l1,time,lc,tc,tw,winel,n)
  to update the collision list after the rescattering of a pair of particles.

6.4 Logical flow of the program

1. Cluster formation: After the wounded nucleons are produced from FRITIOF those participant nucleons from the projectile and target are clustered, separately.
2. Emission of firecracker gluons: Gluons are emitted from those clusters and matched to strings.
3. Bremsstrahlung radiation:
   a) The strings without the RPS gluon are sent into ARIADNE for bremsstrahlung radiation.
   b) A string with the RPS gluon will first compare the hardness of its RPS gluon with that of its firecracker gluon if it happens to have one and the RPS gluon is drowned and replaced by the firecracker gluon if the firecracker gluon is harder. Then the string is sent into ARIADNE for bremsstrahlung radiation.
4. Fragmentation: The strings after bremsstrahlung radiation will go into JETSET for fragmentation.
5. Formation of the initial collision list: The rescattering transport process starts by the creation of the initial collision list.
6. Find next collision: From the collision list the collision with the earliest collision time is selected to perform collision.
7. Move along Newton trajectory: Each particle moves along its own trajectory from the moment of the last collision to the current one.
8. Adjudge and perform collision: Adjudge what kind of scattering (elastic or inelastic) will take place and perform the corresponding scattering.
9. Update collision list: All collisions, in the collision list, involving the scattering particles i or/and j should be removed from the list. The collision list is then updated.
10. Loop: Loop over until no collision pair is left in the collision list.

Remark: If a user wishes to include more rescattering channels besides the 90 channels in present program, he could change the criteria in subroutine 'ctlcre' and the corresponding one in subroutine 'updatl'. At the same time he should also add relevant cross sections and reactions in subroutine 'prod'.

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Appendix A

The following inelastic channels are included in the program(numbers behind are relative cross sections):

a)$\pi + \pi \rightarrow \overline{K} + K$.

1. $\pi^+\pi^- \rightarrow K^+K^-$, 1/2
2. $\pi^+\pi^- \rightarrow K^0\overline{K^0}$, 1/2
3. $\pi^+\pi^0 \rightarrow K^+\overline{K^0}$, 1
4. $\pi^0\pi^0 \rightarrow K^+K^-$, 0
5. $\pi^0\pi^0 \rightarrow K^0\overline{K^0}$, 0
6. $\pi^-\pi^0 \rightarrow K^-K^0$, 1

b) $\pi + N \rightarrow K + \Lambda$.

1. $\pi^-p \rightarrow K^0\Lambda$, 1
2. $\pi^+n \rightarrow K^+\Lambda$, 1
3. $\pi^0p \rightarrow K^+\Lambda$, 1/2
4. $\pi^0n \rightarrow K^0\Lambda$, 1/2

c) $\pi + \overline{N} \rightarrow \overline{K} + \overline{\Lambda}$.

1. $\pi^+\bar{p} \rightarrow \overline{K^0}\,\overline{\Lambda}$, 1
2. $\pi^-\bar{n} \rightarrow K^-\overline{\Lambda}$, 1
3. $\pi^0\bar{p} \rightarrow K^-\overline{\Lambda}$, 1/2
4. $\pi^0\bar{n} \rightarrow \overline{K^0}\,\overline{\Lambda}$, 1/2

e) $\pi + N \rightarrow K + \Sigma$.

1. $\pi^-p \rightarrow K^+\Sigma^-$, 1/9
2. $\pi^-p \rightarrow K^0\Sigma^0$, 2/9
3. $\pi^+p \rightarrow K^+\Sigma^+$, 1

4. $\pi^+ n \to K^+ \Sigma^0$, $\quad 2/9$

5. $\pi^+ n \to K^0 \Sigma^+$, $\quad 1/9$

6. $\pi^0 p \to K^+ \Sigma^0$, $\quad 4/9$

7. $\pi^0 p \to K^0 \Sigma^+$, $\quad 2/9$

8. $\pi^0 n \to K^+ \Sigma^-$, $\quad 2/9$

9. $\pi^0 n \to K^0 \Sigma^0$, $\quad 4/9$

10. $\pi^- n \to K^0 \Sigma^-$, $\quad 1$

f) $\overline{K} + N \to \pi + \Lambda$.

1. $K^- p \to \pi^0 \Lambda$, $\quad 1/2$

2. $K^- n \to \pi^- \Lambda$, $\quad 1$

3. $\overline{K^0} p \to \pi^+ \Lambda$, $\quad 1$

4. $\overline{K^0} n \to \pi^0 \Lambda$, $\quad 1/2$

g) $\overline{K} + N \to \pi + \Sigma$.

1. $K^- p \to \pi^0 \Sigma^0$, $\quad 0$

2. $K^- p \to \pi^- \Sigma^+$, $\quad 1/2$

3. $K^- p \to \pi^+ \Sigma^-$, $\quad 1/2$

4. $\overline{K^0} p \to \pi^+ \Sigma^0$, $\quad 1$

5. $\overline{K^0} p \to \pi^0 \Sigma^+$, $\quad 1$

6. $\overline{K^0} n \to \pi^0 \Sigma^0$, $\quad 0$

7. $\overline{K^0} n \to \pi^- \Sigma^+$, $\quad 1/2$

8. $\overline{K^0} n \to \pi^+ \Sigma^-$, $\quad 1/2$

9. $K^- n \to \pi^0 \Sigma^-$, $\quad 1$

10. $K^- n \to \pi^- \Sigma^0$, $\quad 1$

h) $\overline{K} + N \to K + \Xi$.

1. $K^- p \to K^0 \Xi^0$, $\quad 1/4$

2. $K^- p \to K^+ \Xi^-$, $\quad 1/4$

3. $K^-n \to K^0\Xi^-$, 1

4. $\overline{K^0}p \to K^+\Xi^0$, 1

5. $\overline{K^0}n \to K^0\Xi^0$, 1/4

6. $\overline{K^0}n \to K^+\Xi^-$, 1/4

i) $N + N \to N + \Delta$.

1. $pp \to \Delta^+ p$, 1/3
2. $pp \to \Delta^{++} n$, 1
3. $pn \to \Delta^+ n$, 1/3
4. $pn \to \Delta^0 p$, 1/3
5. $nn \to \Delta^0 n$, 1/3
6. $nn \to \Delta^- p$, 1

j) $\pi + N \to \pi + \Delta$. In the reaction those channels, $\pi^0 p \to \Delta^+\pi^0$, $\pi^- p \to \Delta^0\pi^0$, $\pi^+ n \to \Delta^+\pi^0$ and $\pi^0 n \to \Delta^0\pi^0$ are not included because they have a small relative cross section 1/18.

1. $\pi^+ p \to \Delta^{++}\pi^0$, 1
2. $\pi^+ p \to \Delta^+\pi^+$, 2/3
3. $\pi^0 p \to \Delta^0\pi^+$, 16/27
4. $\pi^0 p \to \Delta^{++}\pi^-$, 4/9
5. $\pi^+ n \to \Delta^{++}\pi^-$, 2/9
6. $\pi^+ n \to \Delta^0\pi^+$, 8/9
7. $\pi^- p \to \Delta^-\pi^+$, 2/9
8. $\pi^- p \to \Delta^+\pi^-$, 8/27
9. $\pi^0 n \to \Delta^+\pi^-$, 16/27
10. $\pi^0 n \to \Delta^-\pi^+$, 4/9
11. $\pi^- n \to \Delta^-\pi^0$, 1
12. $\pi^- n \to \Delta^0\pi^-$, 2/3

k) $\pi + N \to \rho + N$.

1. $\pi^- p \to \rho^0 n$, 2/9

2. $\pi^- p \to \rho^- p$, 1/9

3. $\pi^- n \to \rho^- n$, 1

4. $\pi^+ n \to \rho^0 p$, 2/9

5. $\pi^+ n \to \rho^+ n$, 1/9

6. $\pi^+ p \to \rho^+ p$, 1

7. $\pi^0 p \to \rho^+ n$, 2/9

8. $\pi^0 n \to \rho^0 n$, 4/9

9. $\pi^0 p \to \rho^0 p$, 4/9

10. $\pi^0 n \to \rho^- p$, 2/9

l) $K + \overline{N} \to \pi + \overline{\Lambda}$.

1. $K^+ \bar{p} \to \pi^0 \overline{\Lambda}$, 1/2
2. $K^+ \bar{n} \to \pi^+ \overline{\Lambda}$, 1
3. $K^0 \bar{p} \to \pi^- \overline{\Lambda}$, 1
4. $K^0 \bar{n} \to \pi^0 \overline{\Lambda}$, 1/2

m) $K + \overline{N} \to \overline{K} + \Xi$.

1. $K^+ \bar{p} \to \overline{\Xi^0}\ \overline{K^0}$, 1/4
2. $K^+ \bar{p} \to \overline{\Xi^-} K^-$, 1/4
3. $K^+ \bar{n} \to \overline{\Xi^-}\ \overline{K^0}$, 1
4. $K^0 \bar{p} \to \overline{\Xi^0} K^-$, 1
5. $K^0 \bar{n} \to \overline{\Xi^0}\ \overline{K^0}$, 1/4
6. $K^0 \bar{n} \to \overline{\Xi^-} K^-$, 1/4

n) $\pi + \overline{N} \to \overline{K} + \overline{\Sigma^0}$. The following two reactions have a low reaction rate because of the poor aboundance of $\overline{N}$, so we only include the production of $\overline{\Sigma^0}$ which decays into $\overline{\Lambda}$.

1. $\pi^+ \bar{p} \to \overline{K^0}\ \overline{\Sigma^0}$, 2/9
2. $\pi^- \bar{n} \to K^- \overline{\Sigma^0}$, 2/9
3. $\pi^0 \bar{p} \to K^- \overline{\Sigma^0}$, 4/9
4. $\pi^0 \bar{n} \to \overline{K^0}\ \overline{\Sigma^0}$, 4/9

o) $K + \overline{N} \to \pi + \overline{\Sigma^0}$.

1. $K^+ \bar{p} \to \pi^0 \overline{\Sigma^0}$, 0
2. $K^0 \bar{p} \to \pi^- \overline{\Sigma^0}$, 1
3. $K^0 \bar{n} \to \pi^0 \overline{\Sigma^0}$, 0
4. $K^+ \bar{n} \to \pi^+ \overline{\Sigma^0}$. 1

Appendix B

The following is a sample main program.

```
C..This program generates a few sample  LUCIAE events, and then does
C..histogram for negatively charged particle multiplicity distribution
C..in O+Au collision at 200 GeV/nucleon lab energy.
C..This routine, loaded together with (FRITIOF_7.02R, ARIADNE_4.02R,
C..PYTHIA5.5 and JETSET7.3) can be used to test the installation of programs.
C----------------------------------------------------------------------

      PARAMETER (KSZJ=20000,KSZ1=30)
C...    **** Be sure to check that all the KSZJ's in MAIN, Fritiof,
C...         Jetset and Pythia are identically set      *****
      COMMON/FRPARA1/KFR(KSZ1),VFR(KSZ1)
      COMMON/FRINTN0/PLI0(2,4),AOP(KSZ1),IOP(KSZ1),NFR(KSZ1)
      COMMON/LUDAT1/MSTU(200),PARU(200),MSTJ(200),PARJ(200)
      COMMON/LUJETS/N,K(KSZJ,5),P(KSZJ,5),V(KSZJ,5)
      COMMON/LUDAT3/MDCY(500,3),MDME(2000,2),BRAT(2000),KFDP(2000,5)
      DIMENSION MP(0:300)

C...Open a file to take the write out of the program:
      MSTU(11) = 20
      OPEN(MSTU(11),FILE='test.out',STATUS='unknown')

C::::::Multiplicity distribution for O+AU collision at 200 GeV ::::::::

C...Forbid the decays of Lambda and K_S0:
      MDCY(LUCOMP(3122),1) = 0
      MDCY(LUCOMP(310),1) = 0

C...Book spaces for the histogram (or use a histogram package):
      DO 50 J=0,300
50    MP(J) = 0

C...Test 50 events (of course a lot more events are needed realistically):
      NEVENT=50
      NTRIG = 0
      DO 100 I=1, NEVENT

      CALL FREVENT('FIXT','O','AU',200.)

C...Output the event using JETSET routine LULIST:
      IF(I.LE.3) CALL LULIST(1)

C...Edit the event record, remove partons or decayed particles:
      CALL LUEDIT(1)
```

```
C...Assume a trigger requiring that the energy in the forward cone
C...(theta < 0.3 degree) must be less than 60% of the total beam energy.
C...Also find out the number of negatively charged particles:
      IQTRIG = 0
      EFWD = 0.
      N_=0
      DO 70 J=1, N
      THETA = PLU(J,14)
C...  (PLU is a JETSET function.  Please refer to the JETSET manual.)
      IF(THETA.LT.0.3) EFWD = EFWD+PLU(J,4)

C...Count the negative particles.  Spectator nuclei, which have codes
C...ABS(K(J,2))=10000+N_proton, must be excluded:
      IF(ABS(K(J,2)).LT.10000) THEN
        IF(PLU(J,6).LT.0.) N_ = N_+1
      ENDIF
70    CONTINUE

      EBEAM = 200.*IOP(3)
      IF(EFWD.LT.0.6*EBEAM) IQTRIG = 1

C...Do histogram:
      IF(IQTRIG.EQ.1) THEN
      NTRIG = NTRIG+1
      MP(N_) = MP(N_)+1
      ENDIF

100   CONTINUE

C...Output the histogram data:
      WRITE(MSTU(11),500) NEVENT, NTRIG
      DO 200 J=0,300
200   WRITE(MSTU(11),*) J, FLOAT(MP(J))/FLOAT(NTRIG)
500   FORMAT(X,'Number of events:',I4,2x,'Triggered events:',I4)

C...Write out the values of the parameters and some statistics:
      CALL FRVALUE(0)

      CLOSE (MSTU(11))
      END
```

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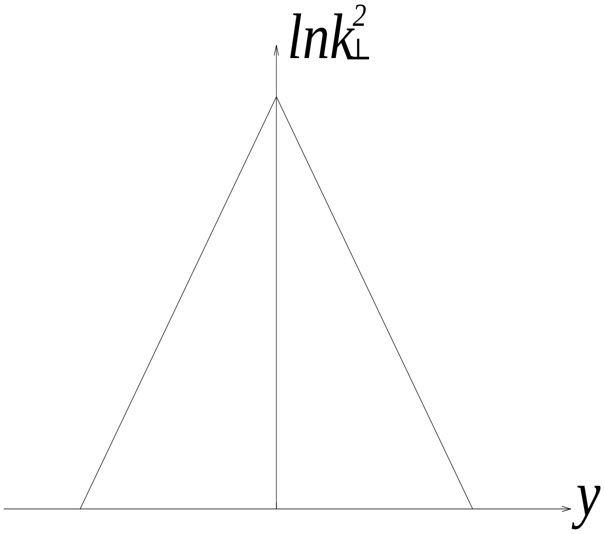

Fig.1a: The phase space limit for the emission of a gluon from a colour dipole with no transverse extension.

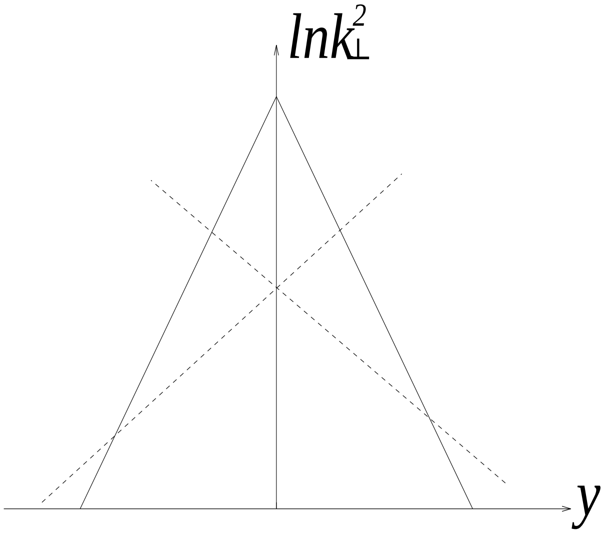

Fig.1b: The available phase space for gluon emission from an extended colour dipole.

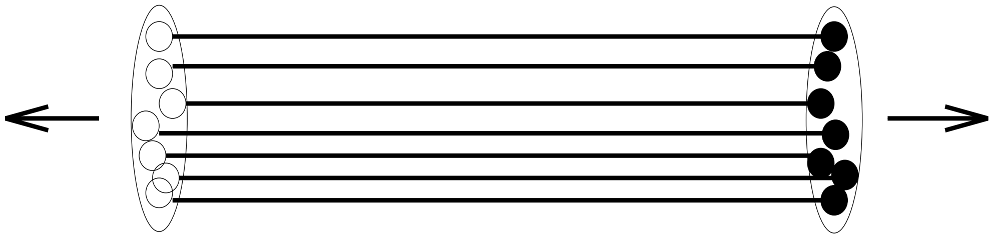

Fig.2: A cluster of nucleons after collisions.