AN EVENT GENERATOR FOR INTERACTIONS BETWEEN HADRONS AND NUCLEI - FRITIOF VERSION 7

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Abstract:

FRITIOF is a Monte Carlo program that implements the Lund string dynamics model for hadron-hadron, hadron-nucleus and nucleus-nucleus collisions. This new version extends from the original low-P_T constructions to include the hard scattering effects and a more refined treatment of the QCD gluon radiation in terms of a soft radiation model in the colour dipole approximation. This paper includes a brief presentation of the model and a description of the program.

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PROGRAM SUMMARY

Title of Program: FRITIOF version 7

Catalogue number:

Program obtainable from: pihong@thep.lu.se (internet), thephp@seldc52 (bitnet)

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

Operating system: ULTRIX RISC 4.2

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: 5200

Keywords: Monte Carlo, hadrons, nuclei, interactions, gluon radiation, Rutherford parton scattering, fragmentation.

Nature of the physical problem: In high energy hadron-hadron, hadron-nucleus and nucleus-nucleus collisions multi particle final states are produced. The bulk of the particles produced are at low P_T. Strong interaction processes are generally non-perturbative and can not yet be fully understood in terms of quantum chromodynamics (QCD). As energy gets higher, some high-P_T phenomena begin to appear in accordance with the perturbative calculations in QCD. The problem is to consistently connect the high P_T Rutherford scattering and the ensuing gluonic bremsstrahlung with a nonperturbative model for the low P_T phenomena.

Method of solution: A collision between two hadrons is modelled by many momentum transfers. The possibility of one of the momentum transfers corresponding to large P_T scattering is properly treated according to QCD. After the exchange of momenta the hadrons are assumed to become two excited string states, which emit further gluonic radiations in a colour dipole approach to the QCD parton branching. The final hadronization is performed by using the Lund string fragmentation model. Collisions with nuclei are assumed to involve only independent collisions between the constituent nucleons.

Restriction of complexity of the problem: The program is not supposed to be applicable at collision centre-of-mass energies ($\sqrt{s}$) below 10 GeV. At very high energies ($\sqrt{s}$ in the TeV range), especially for heavy ion collisions, 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. Some examples:

pp	$\sqrt{s} = 30$ GeV:	$\sim$ 90 events/min
$\bar{p}p$	$\sqrt{s} = 900$ GeV:	$\sim$ 70 events/min
$\bar{p}p$	$\sqrt{s} = 40$ TeV:	$\sim$ 30 events/min
$^{16}\mathrm{O} + {}^{197}Au$	$p_{\mathrm{lab}} = 200$ A GeV/c:	$\sim$ 6 events/min

LONG WRITE-UP

1 Introduction

Hadronic interactions are complex processes that involve many strong and electro-weak phenomena. Although some of the more exotic parts of the processes, such as the production of high-P_T jets or W, Z particles, involve a large mass scale and are well described by perturbative QCD and electro-weak theory, the bulk of the event structure is non-perturbative in nature and can not yet be calculated from first principles. Current understanding of hadronic physics is therefore facilitated to a large extent by phenomenological models. The Monte Carlo implementations of such models are particularly useful to test various theoretical ideas. Good Monte Carlo generators are also invaluable to the implementations at various stages of an actual experiment, from its initial design to the final data analysis.

FRITIOF is a Monte Carlo implementation [1] of a model [2] [3] for hadron-hadron, hadron-nucleus and nucleus-nucleus collisions proposed some five years ago. The basic idea of the model is in a simple picture that a hadron behaves like a relativistic string with a confined colour field similar to the vortex line in a type II superconductor embedded in a superconducting vacuum. The field of such a vortex line is equivalent to that of a chain of dipoles lined up along the vortex line. The dipole links act as partons. During a soft interaction many small transverse momenta are exchanged between the dipole links and two longitudinally excited string states result from the collision. Disturbance of the colour field will in general initialise gluonic radiation according to QCD, which can then be naturally incorporated in this picture by the colour dipole approximation [4]. The final state particles are obtained by fragmenting the string states like the usual strings [5] in a e^+e^- annihilation.

Over the years this model and its extensions to nuclear collisions have been rather successful in describing a large amount of experimental data. However, using the soft interaction picture as outlined above to describe a complete hadronic interaction can only be acceptable at collision centre-of-mass energies of no larger than a few tens of GeV. At higher energies the occurrence of high-P_T jets and the onset of the minijet phenomena [6] clearly dictate new inputs to the model. This version of FRITIOF represents an effort to extend the applicability of the model into the TeV energy regime. It differs from the previous versions mainly by its inclusion of hard interaction effects through PYTHIA [8] and a more refined treatment of gluonic radiations through ARIADNE [9].

The earliest version of FRITIOF was the version 1.6 written in 1986 by Nilsson-Almqvist and Stenlund. A program manual was then published [1]. However since then the program has been modified a number of times under different authorships. Multiple gluon emission was added to the program, and a more refined nuclear collision geometry [12] was put in later. Earlier attempt was also made to implement the hard interaction physics into the model [13]. FRITIOF 6.0 was the most recent version upon which this current program is based. It should be noted that despite of the numerous evolutions with FRITIOF, no updated program manual was written since the earliest publication. Therefore we feel it is a necessity to have a carefully written documentation for this new version.

A detailed description of the model and its comparison with data can be found in ref. [14]. The theoretical construction of the model is briefly presented here in section 2. The extension of the model to collisions with nuclei is summarised in section 3. Descriptions of the program components are given in section 4. An example on how to use the program is given in the appendix.

2 Hadron-hadron interaction

2.1 Soft momentum transfer

In FRITIOF a interacting hadron is looked upon as a string-like object, with its colour force field stretching like a vortex line in a type II superconductor. A vortex line has a hard core surrounded by an exponentially damped field. Two hadrons interact with each other as their fields overlap, and momentum transfers take place. It is assumed that no net colour is exchanged between the hadrons despite of the momentum transfers. So two hadrons with mass m_1, m_2 and with incoming light-cone momenta

$$P_1^i = (p_+, \frac{m_1^2}{p_+}, \vec{0}_T), \quad P_2^i = (\frac{m_2^2}{p_-}, p_-, \vec{0}_T) \tag{1}$$

will emerge as two excited (colour singlet) states after the interaction with new momenta

$$P_1^f = (p_+ + \frac{m_2^2}{p_-} - P_+^f, P_-^f, \vec{Q}_T), \quad P_2^f = (P_+^f, p_- + \frac{m_1^2}{p_+} - P_-^f, -\vec{Q}_T) \tag{2}$$

where the final state components P_-^f and P_+^f are related to the total momentum transfer Q by

$$P_-^f = \frac{m_1^2}{p_+} + Q_-, \quad P_+^f = \frac{m_2^2}{p_-} + Q_+. \tag{3}$$

Assuming incoherence in the collision process, the total momentum transfer Q in FRITIOF is a sum of many momentum exchanges among the quanta of colour field,

$$Q = \sum_j k_j. \tag{4}$$

Furthermore if the quanta obey Feynman's wee parton spectrum the total longitudinal momentum components should follow the distribution

$$dP \propto \frac{dP_-^f}{P_-^f}\frac{dP_+^f}{P_+^f}. \tag{5}$$

The transverse components of the k_j's are in general rather small and pointing at random directions. Similar to a random walk in the transverse plane, $\vec{Q}_T = \sum \vec{k}_{jT}$ is expected to obey a Gaussian distribution with the average $< Q_T >$ on the order of hadronic mass scale. This completes the FRITIOF description of the momentum transfers in soft hadronic interaction. There are also situations when one or more of the k_j's have a large transverse component. This corresponds to Rutherford parton-parton scattering. One can also expect that the Gaussian spectrum for the soft transverse momentum exchange Q_T should acquire a tail that joins smoothly with the high-P_T QCD spectrum. These effects will be discussed in section 2.2.

The phase space for P_-^f and P_+^f are specified by the kinematical constraints

$$\begin{aligned} P_-^f(p_+ + \frac{m_2^2}{p_-} - P_+^f) &\geq m_1'^2 + Q_T^2, \\ P_+^f(p_- + \frac{m_1^2}{p_+} - P_-^f) &\geq m_2'^2 + Q_T^2, \end{aligned} \tag{6}$$

where m_1' and m_2' are the minimum masses for the excited hadron states. m_1' and m_2' will be assumed to take the values of the initial hadron masses. Technically there are some problems in fragmenting strings of small invariant masses. To avoid such problems a mass parameter m_d, which is somewhat larger than m', is used in the program. A string with mass less than m_d is not treated with string fragmentation, instead it is simply set back to the original hadron mass shell. Such type of events resemble the diffractive events observed experimentally. For this reason m_d will be called "diffractive mass". Obviously, only the diffractive and low multiplicity event samples would be sensitive to this parameter. For most applications m_d will have little effect.

2.2 Rutherford parton-parton scattering

When one of the momentum transfers in eq. (4) has a large transverse component, it corresponds to Rutherford parton-parton scattering (RPS). The differential cross section for the elastic parton-parton scattering is giving by perturbative QCD

$$\begin{aligned} q_1^+ q_2^- \frac{d\sigma}{dq_1^+ dq_2^- dq_T^2} &= \sum_{ij} x_1 f_i(x_1, Q^2)\, x_2 f_j(x_2, Q^2)\, \frac{d\hat{\sigma}_{ij}}{d\hat{t}}(\hat{s}, \hat{t}, \hat{u}) \\ &\quad \cdot \delta(q_T^2 - \frac{\hat{t}\hat{u}}{\hat{s}})\, \delta(x_1\sqrt{s} - q_1^+ - \frac{q_T^2}{q_2^-})\, \delta(x_2\sqrt{s} - q_2^- - \frac{q_T^2}{q_1^+}), \end{aligned} \tag{7}$$

where $\hat{s}$, $\hat{t}$ and $\hat{u}$ are the usual Mandelstam variables describing the kinematics of the parton process, and s is the total centre-of-mass energy squared of the hadron-hadron system. The q_1^+ and q_2^- are the light-cone momentum components of the two outgoing partons. The partons are taken to be massless and on shell. This QCD spectrum is dominated by contributions from the semihard regime where the parton energy fraction x is small, and the dominating structure function behave roughly as $f(x) \sim 1/x$, which is essentially the Feynman's spectrum for wee partons. This means that the distribution in eq. (5) should be preserved even when hard scattering occurs. A truly hard scattering gives a strong kick to the string end or interior, and produces gluon kinks on the string. The momentum for the string as a whole should then satisfy the condition

$$P_-^f > q_1^-, \quad P_+^f > q_2^+ \tag{8}$$

in addition to the restraints in eq. (6). Furthermore the Gaussian behaviour of the transverse component of $\vec{Q}_T$ will be superimposed by a hard $\vec{q}_T$ given by eq. (7).

The applicability of eq. (7) is limited under strong kinematical constraints as P_T gets smaller, and it diverges in the infrared limit. The way to handle these difficulties is crucial to a model that deals with hard as well as soft interactions. The divergence problem can be handled by a probabilistic approach involving a Sudakov probability factor, such that the distribution for the hardest RPS is given by

$$Prob(q_T) = \rho(q_T) \exp\left(- \int_{q_T}^{\sqrt{s}/2} dq_T' \rho(q_T') \right), \tag{9}$$

where $\rho(q_T) = (d\sigma/dq_T)/\sigma_{nd}(s)$ with $\sigma_{nd}(s)$ being the hadron-hadron non-diffractive inelastic cross section. The Sudakov factor in the exponential function is interpreted as the probability of having no RPS harder than q_T. Such an approach can be found in ref. [7] which has been implemented in the PYTHIA program [8]. FRITIOF uses PYTHIA to generate the Rutherford parton-parton scattering.

Since the event structure is dominated by the hardest momentum transfer, FRITIOF includes only the hardest RPS generated according to eq. (9).

With the above approach we obtain a unitarized RPS distribution. Still not all the RPS generated from eq. (9) should be accepted. During the collision process there is colour excitation in the nucleon states and consequently there is gluon bremsstrahlung radiation according to QCD. In the picture of QCD parton model eq. (7) is applicable only to the momentum transfer which is hardest compared with the associated bremsstrahlung gluons. We therefore adopt a procedure that compares the "hardness" of the Rutherford partons generated from eq. (9) to that of the bremsstrahlung gluons. The RPS is accepted only if it is harder than the associated radiation. If the RPS is "drowned", which is to say that it is softer than the radiation, then the RPS is not acceptable and the collision proceeds as a purely soft collision. With this prescription the RPS spectrum is suppressed smoothly at small to medium q_T. This "drowning" mechanism is critical to the merging of hard and soft interactions in FRITIOF. The treatment of gluon radiation and the prescription for the RPS drowning will be presented in more detail in the next section.

To make it clearer to see the difference between a RPS event and a purely soft event, it is useful to write the momentum of the nucleon as a sum of two terms

$$P^f = P_{soft} + q, \tag{10}$$

where q is the momentum of the hard scattered parton, and P_{soft} is the momentum of the remnant. In this paper q will be referred as the "hard momentum" and P_{soft} will be termed the "soft momentum". In terms of P_{soft}, the distribution in eq. (5) can be rewritten as

$$dP \propto \frac{dP^-_{soft,1}}{P^-_{soft,1} + q_1^-} \frac{dP^+_{soft,2}}{P^+_{soft,2} + q_2^+}. \tag{11}$$

This means that RPS introduces a bias in the soft momentum distribution. Collisions having very hard scattering would in general also have larger than usual components of P_{soft}. This feature in FRITIOF results in, for example, higher than average multiplicity and transverse energy flows in events containing RPS.

2.3 The state of the excited strings and the gluon radiation

The outcome of the interaction prescribed above is two excited colour singlet string states. In the absence of hard scattering or gluon radiations such states are just two longitudinal string states with the valence constituents of the hadrons (quark-antiquark for mesons and quark-diquark for baryons) attached to the end points. The end points will be given a (primordial) transverse momentum distributed according to a Gaussian. The momenta for the two end partons Q_1 and Q_2 can be easily figured out given that they share the total soft momentum of the system. For instance for a projectile nucleon, the plus component for the diquark momentum is

$$\begin{aligned} Q_2^+ &= \frac{1}{2P^-_{soft}} \Big\{ (P^+_{soft}P^-_{soft} + Q^2_{2T} - Q^2_{1T}) \\ &\quad + [(P^+_{soft}P^-_{soft} + Q^2_{2T} - Q^2_{1T})^2 - 4P^+_{soft}P^-_{soft}Q^2_{2T}]^{1/2} \Big\} \end{aligned} \tag{12}$$

where the transverse momentum Q_{2T} is generated from a Gaussian distribution. The inclusion of multiple gluon emission or the hard scattering produces "kinks" on the string which results in "bent" strings. As energy increases such effects become stronger, and so it is of critical importance to treat them properly.

A high mass string state will have associated gluon bremsstrahlung. Such emission of multiple gluons can be treated conveniently as a parton branching process. In FRITIOF we use the colour dipole approximation [4], *i.e.*, a string is treated as a colour dipole, it splits into two dipoles after emitting one gluon, and the two dipoles go on to emit gluons independently and more dipoles are formed to result in a cascading process. Such a scheme has already been implemented with success in the ARIADNE Monte Carlo program [9], which is then incorporated into FRITIOF to perform the gluon bremsstrahlung radiation.

Complication arises since a hadron is an extended object. During interaction it is acted upon by many small momentum transfers over an extended space-time region, and therefore the source responsible for the emission has certain finite size rather than being point-like as in e^+e^- annihilation. Radiation from an extended source is treated in FRITIOF in terms of the Soft Radiation Model (SRM) [11]. In SRM, it is assumed that, similar to an emitting antenna, radiation of wavelengths shorter than the source size would be damped due to destructive interference. In a Lorenz frame where a gluon with transverse momentum k_T is emitted at a right angle to momenta of the string end points, the gluon wavelength is $\lambda \sim 1/k_T$. Introducing a parameter μ_0 to characterise the inverse of the source size, then only a piece of the source, with energy fraction

$$a(k_T) = \left(\frac{\mu_0}{k_T}\right)^\alpha , \tag{13}$$

can radiate coherently, where α is a parameter characterising the dimensionality of the source. This mechanism [11] reduces the available phase space for radiation from an extended source as compared to a true point energy source. The phase space for the emitted gluon can be represented approximately in the rest frame of the string by

$$k_T e^{\pm y} \lesssim a(k_T) M, \tag{14}$$

where M is the invariant mass of the emitting dipole. In FRITIOF α is set to unity, consistent with the assumption that the energy density has one-dimensional string-like shape. μ_0 is an adjustable parameter in the model, and its value is around 0.7 GeV corresponding to a transverse extension of the source $\pi/\mu \sim 0.9 fm$.

For a string that comes out of a purely soft collision, the excited string as a whole acts coherently for gluon emission, and here the inverse of μ_0 represents the transverse extension of the whole string. There are also situations when the two string ends should be treated separately, with each end having its own extension. The two ends are then characterised by two numbers μ_1 and μ_2. The suppression of phase space becomes $k_T^2 e^{-y} \lesssim \mu_1 M$, $k_T^2 e^{y} \lesssim \mu_2 M$. In FRITIOF such situation arises in a RPS event. The presence of a Rutherford gluon effectively breaks down the colour coherence on the string as a whole, and the two string ends act independent of each other as coherent emitters. mu_1 and μ_2 are interrelated here as the extensions of the two string ends are expected to add up to give the extension of the whole string. If r is the fraction of the total extension at one end, then

$$\mu_1 = \mu_0/r, \qquad \mu_2 = \mu_0/(1-r) \tag{15}$$

with $r \in (0, 1)$. The choice of r is rather arbitrary. In a simple scenario one can expect that the two string ends each takes half of the string transverse extension and therefore $r \approx 1/2$. One can also imagine that the extensions of the two ends are not exactly half and half but rather they are distributed in certain way that relates to the overlap of the two strings. r may be uniformly distributed for example. The model is not very sensitive to these choices.

In a RPS event, hard scattered partons represent well localised energy density on the string, and the emission from this parton is not subject to the suppression of the SRM. The large and localised momentum transfer would also bend the string, so that gluon kinks are formed before the cascade develops. The presence of these kinks gives extra folds of phase space to the gluon radiation, which means more gluonic activities in the cascade. In the following we discuss the situation with valence quarks and gluons. Sea quarks represent a relatively small contribution in comparison to the gluons and in the current FRITIOF they are treated simply as gluons.

In case the hard scattered parton is a valence quark, which always corresponds to a string end in FRITIOF, the string end suffers a violent kick and the string is bent and consequently a gluon kink is formed on the string. The string configuration, taken a baryon as an example, is then q_h-g_s-qq_s, where the symbol q_h represents a hard quark, g_s a soft gluon kink and qq_s a soft diquark. The word "soft" here means that they will be treated in the Soft Radiation Model as extended objects. The soft momenta are partitioned as in eq. (12) and so g_s has momentum Q_1 and qq_s has momentum Q_2.

At high energy RPS is dominated by gluon scattering. A hard scattered gluon is expected to stick out somewhere in the interior of the extended region which was acted upon by many soft momentum transfers. This region would then be split into two parts by the presence of the hard gluon. This results in a kink in the interior of the string which acts as an extra gluon. The string configuration becomes q_s-g_h-g_s-qq_s. Here q_s is the trailing quark end, g_h is the hard gluon, g_s is the soft gluon kink and qq_s is the leading diquark end. As usual the soft momentum P_{soft} is partitioned into two terms Q_1 and Q_2. The diquark qq_s has the momentum Q_2, while the the kink g_s takes a fraction r' of the momentum Q_1, and the quark q_s gets a momentum $(1-r')Q_1$. This energy fraction r' is assumed to take a distribution

$$\frac{dr'}{r' + \frac{q_-}{P_-^f}} \tag{16}$$

for the projectile string, and a corresponding expression with the plus momentum components is used for the target. where q_T is the transverse momentum of the Rutherford gluon and M_T is the transverse mass of the string system. We further assume the extension of the string piece is proportional to its energy. The three extended partons are then assigned the following values to the SRM suppression parameter: $\mu_0/r(1-r')$ for q_s, μ_0/rr' for g_s and $\mu_0/(1-r)$ for qq_s.

We have specified the possible string configurations as a result of the hadronic collision. Such string states will then proceed to a dipole cascade emission. As mentioned in section 2.3, the bremsstrahlung gluons provide a background noise in which the Rutherford partons may become "drowned". In case this happens the RPS must be rejected and replaced by a purely soft event. To quantify this we need to define a measure for the "hardness" of the Rutherford partons and the bremsstrahlung gluons. We use an invariant $\mathcal{P}_T$ defined in terms of the invariant masses of the parton systems as

$$\mathcal{P}_T^2 = \frac{s_{12}s_{23}}{s_{123}}. \tag{17}$$

Here 2 is the parton in question, and 1 and 3 are the two partons neighbouring to 2 in the dipole chain. This definition of invariant $\mathcal{P}_T$ is also used as the ordering variable in the ARIADNE dipole cascade program [9]. With this definition, the acceptable RPS must satisfy the condition

$$\mathcal{P}_T^R \geq \mathcal{P}_T^b \geq \mathcal{P}_T^{cut}, \tag{18}$$

where $\mathcal{P}_T^R$ is the invariant $\mathcal{P}_T$ of the Rutherford parton, $\mathcal{P}_T^b$ is the invariant $\mathcal{P}_T$ of the hardest bremsstrahlung gluon emitted from the string system, and $\mathcal{P}_T^{cut} = 0.5 \sim 1$ GeV is the ARIADNE cut off parameter for the minimum invariant $\mathcal{P}_T$ in a dipole cascade. The RPS is drowned when the condition above is not satisfied. Most of the RPS with small or moderate q_T will become drowned. In this way a feature of infrared stability is realised in FRITIOF. The QCD spectrum is largely suppressed at small q_T as a result of the drowning. A cut off parameter q_{Tmin} which is normally needed in connection to eq. (7) becomes essentially irrelevant in FRITIOF. The effect of this "drowning" mechanism on the event structure is quite substantial. As an example at $\sqrt{s} = 900$ GeV, roughly 70% of the RPS generated from eq. (9) become drowned and therefore only 30% or less of the events can be characterised as RPS events.

The dipole cascade stops when the invariant $\mathcal{P}_T$ of the possible emission becomes lower than the cut off $\mathcal{P}_T^{cut}$. The final step is fragmentation. The string fragmentation scheme [5] as implemented in the Lund Monte Carlo JETSET 7.3 [15] is used. The fragmentation parameters there are tuned to fit the e^+e^- data. These fragmentation properties, however, should also be applicable to the strings formed in hadronic collisions due to the assumption of jet universality.

3 Hadron-nucleus and nucleus-nucleus collisions

The generalisation of the model to hadron-nucleus and nucleus-nucleus collisions is rather straightforward. At high energies a collision between nuclei can be regarded as incoherent collisions between their nucleons. Thus a nucleon from the projectile interacts independently with the encountered target nucleons as it passes through the nucleus. Each of these sub-collision can be treated the same way as a usual hadron-hadron collision. A crucial assumption made here is that although the nucleon becomes excited as a result of consecutive collisions with target nucleons, it remains essentially a nucleonic state as it traverses the target. This is to say that, on the time scale of the collision process, the excited nucleonic state does not fragment in the intermediate stage and so there is no intra nuclear cascade. This assumption is reasonable at high energy since the time scale associated with fragmentation is expected to be much longer due to time dilation as compared to the traverse time for the nucleon passing through the nucleus. So in this picture a projectile nucleon passing through the nucleus will exchange momentum according to eq. (5) each time it encounters a target nucleon. 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 have associated bremsstrahlung radiations and finally fragment into hadrons.

One important aspect of the collision is the nuclear collision geometry. This part of the program was originally written by Ding and Stenlund and is basically unchanged in the current version. The only modifications made are the implementation of energy-dependent N-N cross sections and some reorganisation of common blocks. In this article we present only briefly the parametrizations used in the program. For a detailed description on the nuclear collision geometry, users are referred to ref. [12].

During a collision it is assumed that the projectile passes through the target nucleus on a straight line geometry. If the nucleons are distributed inside the nucleus according to $\rho(r)$, the impact parameters of the incident nucleon to each of the target nucleons can be calculated. The probability of whether there will be interaction between two nucleons is related to the impact parameter through the nucleon-nucleon overlap function $G(b)$. A set of target nucleons that would interact with the incident nucleon can thus be predetermined. Here the incident nucleon is assumed to impinge on the target nucleus at a random impact parameter.

Some modifications are needed for the above prescription when RPS is included. When a nucleon system contains a hard parton, the system would have a rather large P_T and the system centre of mass would then not move on a straight line afterwards. This does not cause real difficulties though. It is assumed that the hard parton would not have further interaction, and therefore it is only the remnant that moves forward and exchanges momentum with the next nucleon. From this viewpoint the collision geometry is entirely preserved.

Since the sub-collisions are assumed to be independent, it is possible for each of them to have RPS. Such multiple hard scattering is a rather complicated process and a proper treatment should include a usage of multi parton structure functions. Within the framework of FRITIOF the treatment is simplified by assuming that the hard interactions are independent. Upon each N-N sub-collision, RPS is generated by regarding the excited (remnant) nucleon state as a ground state nucleon. The "drowning" procedure can be applied at each N-N sub-collision. That is, the RPS is accepted only if it is harder than the hardest bremsstrahlung gluon. It is straightforward to use an iterative procedure to implement this sequence of N-N collisions.

The excited string system now includes the possibility of having several hard partons. The procedure of configuring the string in the hadron-hadron interaction scenario can be extended easily to cover this situation. We requires that the presence of the extra gluons does not inhibit the possible gluon radiations. We therefore first pick up the hardest gluon and configure the string exactly as in the case for hadron-hadron collision. The cascade would then allowed to develop and the rest of the gluons are one by one inserted into the cascading sequence in a P_T and rapidity ordered fashion. The assumption of ordering in rapidity is to make the string in some sense as "short" as possible, which is related to the infrared stability on Lund strings. Other aspects of the model remain essentially the same as that for hadron-hadron collisions.

In the following we list some of the parametrizations used in connection to the nuclear collision geometry. The nucleon density distribution used in the program is the Wood-Saxon type for heavier nuclei with atomic number $A > 16$,

$$\rho(\vec{r}) = \frac{\rho_0}{1 + \exp\left(\dfrac{r - r_0 A^{1/3}}{C}\right)}, \tag{19}$$

where r_0 is a radius parameter, C is the diffuseness parameter, and ρ_0 is a normalisation constant. r_0 has been taken to be slightly A-dependent and is parametrized as

$$r_0 = 1.16(1 - 1.16A^{-2/3})\ \mathrm{fm}. \tag{20}$$

C is also taken to be slightly A-dependent and its values used in the program ranging from 0.47-0.55 fm. For lighter nuclei with $A \leq 16$, a harmonic oscillator shell model density is used,

$$\begin{aligned} \rho(\vec{r}) &= \frac{4}{\pi^{3/2} d^3}\left[1 + \frac{A-4}{6}\left(\frac{r}{d}\right)^2\right] e^{-r^2/d^2}, \\ d^2 &= \left(\frac{5}{2} - \frac{4}{A}\right)^{-1} \left(< r_{ch}^2 >_A - < r_{ch}^2 >_p\right), \end{aligned} \tag{21}$$

where $< r_{ch}^2 >_A$ and $< r_{ch}^2 >_p = 0.656$ fm^2 are the mean squared charge radii of the the nucleus and proton, respectively. The values used in the program for these radius parameters are taken from the measurements of lepton-nucleus scattering experiments [16]. The nucleons in a nucleus are not supposed to come infinitely close to each other. A parameter R_{min} is used in the program to specify the minimum allowable distance between two nucleons.

For the inelastic overlap function three choices exist in the program:

1. eikonal-type overlap function
$$\begin{aligned} G(b) &= 1 - \exp(-2\Omega(b)), \\ \Omega(b) &= \Omega_0 \exp(-\beta b^2); \end{aligned} \tag{22}$$

2. Gaussian overlap function
$$G(b) = 1 - \left[1 - g_0 \exp(-\gamma b^2)\right]^2; \tag{23}$$

3. gray disk
$$G(b) = \begin{cases} \alpha & b < R \\ 0 & b > R \end{cases} \tag{24}$$

There are two parameters in each of the parametrizations above. They are determined by fitting the total and inelastic cross sections,

$$\begin{aligned} \int d^2b\, G(b) &= \sigma_{inel}, \\ 2\int d^2b\, \Gamma(b) &= \sigma_{tot}, \qquad \text{with } \Gamma(b) = 1 - \sqrt{1 - G(b)}. \end{aligned} \tag{25}$$

As energy gets beyond the ISR range one needs to take the rising of the cross sections into account. In the program the cross section fit No. 8 and the slope parameter fit No.2 of Block and Cahn [17] are used as the input. The Block and Cahn fit includes the CERN collider data and predicts a constant total cross section at ultra-high energies. The total and elastic cross sections from the fits are in good agreement with data up to Tevatron energy.

4 Description of the program

FRITIOF 7 is a subroutine package for simulating events of hadron-hadron, hadron-nucleus, or nucleus-nucleus collisions at high energies. A user is expected to construct his own main program, in which he must set up a specific collision environment and kinematics through the variables in the main subroutine FREVENT and also through certain common blocks. One event is generated each time FREVENT is called. The full information on the event is stored in common block LUJETS, through which the user may design specific trigger condition and perform statistical analysis. The subroutine FREVENT and a few common blocks are normally all that a user needs to know. These are described in more detail in section 4.1. Some of the lesser used common blocks are described in section 4.2. There are also a large number of service subroutines, which are used only internally and may not be of interest to most users. These are listed nevertheless in section 4.3 for completeness.

The program works in the following manner. After initialisation, first a set of subroutines are called to generate the nuclear collision geometry. The designated nucleons are then arranged in subroutine FRRINGO to start off the collision sequence. At this stage FRHARDP is called to generate hard scattering and the soft momentum transfers. After momenta for all the wounded nucleons and their partons have been determined, they are given an appropriate string configuration in subroutine FRATLEO, which calls ARIADNE for gluon radiation. Finally the JETSET routine LUEXEC is called for fragmentation.

The program is written in FORTRAN 77, with the exception that subroutine and common block names of non-standard lengths are used. The random number generator is supplied by the JETSET function RLU [15]. FRITIOF 7 should be loaded together with JETSET 7.3 [15], PYTHIA 5.5 [8], and ARIADNE 3.3r [9] (for FRITIOF 7.01) or ARIADNE 4.02r [10] (for FRITIOF 7.02). To ensure a proper execution the correct version numbers of these companion programs must be observed. Since all these Lund programs share a common block LUJETS as the event record, users should also make sure that the same dimension size is specified for LUJETS in all the relevant programs on sites.

Update history for FRITIOF version 7

- Version 7.01: A new implementation of Rutherford Parton Scattering is the main change as compared to earlier versions. Adaptations made to run with JETSET 7.3, PYTHIA 5.5 and ARIADNE 3.3.
- Version 7.02: ARIADNE version 4.02 is adopted to replace the older version 3.3. Gluon splitting into $q\bar{q}$ pairs and photon emission in the dipole cascade, preciously forbidden for technical reasons, are now allowed.

4.1 User interface

This section contains the minimum information a user must know about the program, namely the main subroutine FREVENT, the common block FRPARA1 for input parameters and and switch controls, and the event record LUJETS. The collision environment is set up by specifying the variables in FREVENT, and then events are generated by calling FREVENT repeatedly.

- SUBROUTINE FREVENT(FRAME,BEAM,TARGET,WIN)

  Purpose: to administrate the generation of one complete event.

  FRAME: character variable to specify the frame of the experiment.

  = 'FIXT' : fixed target experiment, with beam particle momentum pointing in +z direction.

  = 'CMS' : centre of momentum frame, with beam momentum in the +z direction and target momentum in the −z direction.

  BEAM, TARGET: character variables to specify the beam and target hadrons and/or nuclei.

  For BEAM and TARGET the following selections are available:

  'P' proton

'D' deuteron (A=2)

'HE' helium (A=4)

'BE' beryllium (A=9)

'B' boron (A=11)

'C' carbon (A=12)

'O' oxygen (A=16)

'AL' aluminium (A=27)

'SI' silicon (A=28)

'S' sulphur (A=32)

'AR' argon (A=40)

'CA' calcium (A=40)

'CU' copper (A=64)

'AG' silver (A=108)

'XE' xenon (A=131)

'W' Tungsten (A=184)

'AU' gold (A=197)

'PB' lead (A=207)

'U' uranium (A=238)

The following particles are allowed for BEAM only:

'N' neutron

'PBAR' anti-proton

'PI+' positive pion

'PI−' negative pion

'K+' positive kaon

'K−' negative kaon

'NEW1' user-specified hadron or nucleus. The following additional parameters must be specified by the user through common block FRCODES.

If 'NEW1' is a hadron, enter its KF code [18] in KCD(1) and its charge in NPROT(1). For this 'NEW1' hadron, its minimum excitation mass m' and "diffractive" excitation mass m_d are set by default to the hadron mass. If adjustment is needed these two parameters can be set by user in EXMA(1,1) and EXMA(1,2). Furthermore if 'NEW1' is to collide with a nucleus, user may wish to assign the 'NEW1'-nucleon total and elastic cross sections in VFR(17-18) through common block FRPARA1.

If 'NEW1' is a nucleus, enter the nuclear A and Z parameter in NNUC(1) and NPROT(1) respectively. The nuclear size parameters must also be specified: for A$\leq$ 16, enter the root mean squared charge radius $< r_{ch}^2 >^{1/2}$ in RO1(1,1); for A$>$ 16, specify the values of r_0 and C in RO1(1,1) and RO1(1,2). r_0 and C are the parameters for the Wood-Saxon nucleon density.

For TARGET only:

'NEW2' user-specified nucleus. Additional parameters in the following must be specified by the user.

Enter the nuclear A and Z parameters in NNUC(2) and NPROT(2) respectively. Furthermore, if A$\leq$ 16, enter the root mean squared charge radius $< r_{ch}^2 >^{1/2}$ in RO1(2,1), otherwise specify the parameters r_0 and C for the nucleon density function in RO1(2,1) and RO1(2,2).

WIN: specifies the collision energy. More specifically, for FRAME='FIXT', WIN is the laboratory momentum of the beam particle (per nucleon) in GeV/c; for FRAME='CMS', WIN is the (nucleon-nucleon) CMS energy in GeV.

Remark: FRITIOF reinitialises itself whenever the arguments in FREVENT is changed. This feature allows the possibility to mix different types of collisions in one single run. The character variables FRAME, BEAM and TARGET are case insensitive.

The switch controls and adjustable parameters are contained in the common block FRPARA1. These input parameters are provided with sensible default values. The physics presented in section 2 is installed in the program as the default choices. Numerous options are also included to make the program more adaptive and flexible.

- PARAMETER (KSZ1=20)
  COMMON/FRPARA1/KFR(KSZ1), VFR(KSZ1)

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]: VAR(1)=0.20, VAR(3)=1.0, PARJ(21)=0.37, PARJ(41)=0.18, PARJ(42)=0.34.

=2 Set to the values optimised by DELPHI collaboration: VAR(1)=0.22, VAR(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) If set to 1, the outcome of each event will be checked for charge and energy-momentum conservation.

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=0.30 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 parametrization of Block and Cahn [17] (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.

Remark: More variations in the physics controls can be accessed by directly setting up PYTHIA parameters. For example MSTP(33) sets up a K factor in Rutherford parton scattering cross sections, MSTP(51) offers various choices of structure functions, and MSTP(82) selects different scenarios for multiple interactions.

The event generated must be stored and be accessible to users for event analysis. This purpose is served in FRITIOF by adopting the JETSET common block LUJETS. This allows the full advantage of an easy access to a large number of very useful JETSET event analysis subroutines. The documentation on JETSET [15] should be consulted if the user is not already familiar with LUJETS and the event analysis routines built around it.

- PARAMETER (KSZJ=4000)
  COMMON/LUJETS/N,K(KSZJ,5),P(KSZJ,5),V(KSZJ,5)

Remark: briefly, N gives the number of lines in the K, P and V matrices which are filled in the current event. K matrix contains the particle status codes and history information. P matrix gives the momentum, energy and mass of the particle. V matrix contains information about the production vertex. Refer to JETSET manuel [15] for detailed explanation. There is one non-standard code in FRITIOF for nuclear spectator, as explained in the following.

Codes for nuclear spectators: Spectator fragmentation is not included in the current version. However the total momentum of the spectators from either the projectile or target is included and occupies one line in LUJETS. This line is given a special code
K(J,2) $= \pm(10000 + N_p)$,
where the '+' sign denotes for projectile and '$-$' sign for target, and N_p is the number of

the protons in the spectator. The P matrix provides information on the total momentum, energy, and mass of the projectile/target spectator nucleons. Note that because this is not a standard code in JETSET, when an event is listed with JETSET routine LULIST, this line will appear without a character name, and certain JETSET functions such as PLU(J,6), which supposedly gives the charge of a particle, will not work on this line. Special treatment should be applied to this line when the spectator is included in the event analysis.

Remark on the memory size: The size of LUJETS is specified in FRITIOF by a parameter KSZJ. Its current value of 4000 may not be sufficient for storing the products of heavy ion collisions of a few 100's A GeV in energy. One then need to expand LUJETS to a larger size. The system parameters must be consulted to make sure the size does not exceed the system limit. When making the change, corresponding changes to LUJETS must be made in ALL companion program packages (JETSET, PYTHIA), and in addition new value must be given to the parameters MSTU(4) in JETSET.

4.2 Other common blocks

A few other common blocks exist in the program which contain some relatively useful information. These common blocks are listed in the following.

- COMMON/FRCODES/IPT(2),PACD(27),NNUC(27),NPROT(27),KCD(27), RO1(27,2),EXMA(9,2)

Remark: Here it stores a list of particles/nuclei available in FRITIOF and their relevant data. It is possible for users to adjust the nuclear density parameters and the minimum and diffractive excitation mass parameters through this common block.

IPT(L): a pointer which gives the location of the selected projectile (L=1) and target (L=2) particles on the PACD array. For example, if user selects O+Au collision, IPT(L=1,2) will then have values 15 and 25.

PACD(I): The default values are given below in order of I from 1 to 27:

```
'NEW1','NEW2','PI+ ','PI- ','K+  ','K-  ','N   ','P   ','PBAR',
'D   ','HE  ','BE  ','B   ','C   ','O   ','AL  ','SI  ','S   ',
'AR  ','CA  ','CU  ','AG  ','XE  ','W   ','AU  ','PB  ','U   '.
```

NNUC(I): gives A, the number of nucleons in the particle/nucleus corresponding to PACD(I). Note for all the hadrons including the mesons, this number is 1. NNUC(I=3-27) are provided with default values. NNUC(1-2) must be entered by user if 'NEW1' or 'NEW2 'is selected as the BEAM/TARGET in subroutine FREVENT.

NPROT(I): gives Z, the number of protons or the charge of the nucleus/particle corresponding to PACD(I). NPROT(1-2) must be entered by user if 'NEW1' or 'NEW2' is selected in FREVENT.

KCD(I): gives the KF code [18] of the particle in PACD(I). Default values are
0, 0, 211, -211, 321, -321, 2112, 2212, -2212, 0 (I$\geq$ 10).
KCD(I) is a irrelevant number when corresponding to a nucleus. It becomes necessary for users to enter values for KCD(1-2) only when 'NEW1' or 'NEW2' selected as the BEAM/TARGET is a hadron.

RO1(I,L): gives the parameters of the nuclear density distribution for the corresponding nucleus PACD(I). RO1 is irrelevant when corresponding to hadrons. For nuclei with $A \leq 16$, RO1(I,1) is the root-mean-squared radius of the nuclear charge distribution, and RO(I,2) is irrelevant. For nuclei with $A > 16$, RO(I,1) and RO(I,2) give the radius parameter r_0 and the edge thickness parameter C for the Wood-Saxon nucleon density distribution. The following values are used as default:
RO1(I,1) (I=1,27) = 0., 0., 0., 0., 0., 0., 0., 0., 0., 2.095, 1.74, 2.519, 2.37, 2.446, 2.724, 1.01, 1.014, 1.027, 1.045, 1.045, 1.076, 1.101, 1.108, 1.118, 1.120, 1.122, 1.125;
RO1(I,2) (I=1,27) = 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0.478, 0.480, 0.490, 0.490, 0.490, 0.490, 0.495, 0.52, 0.530, 0.540, 0.545, 0.55.
Note the numbers given are in fermi. Again when user selects a new nucleus through NEW1 or NEW2 as the BEAM/TARGET, he must enter the corresponding nucleon density parameters in RO1.

EXMA(I,L): gives the parameters for the minimum excitation mass (L=1) and the diffractive excitation mass (L=2) corresponding to the first nine hadrons on the list of PACD(I). Default values (in GeV) are as follows.
EXMA(I,1) (I=1,9) = 0., 0., 0.14, 0.14, 0.50, 0.50, 0.94, 0.94, 0.94;
EXMA(I,2) (I=1,9) = 0., 0., 0.40, 0.40, 0.75, 0.75, 1.20, 1.20, 1.20.
In the program, the minimum excitation mass is enforced to be larger than the initial hadron mass.

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.

- PARAMETER (KSZ1=20)
  COMMON/FRINTN0/PLI0(2,4),AOP(KSZ1),IOP(KSZ1),NFR(KSZ1)

PLI0(L,J): initial momenta of the colliding hadron/nucleon.
L=1,2 stands for projectile and target, respectively; J=1,4 give light-cone components of the momentum P_x, P_y, P_- and P_+.

AOP(I): provides some information for the current event.

I=1: the total centre-of-mass energy of initial projectile-nucleon collision system.

I=2: impact parameter (in fermi) of the collision.

I=3-4: the parameters Ω_0 and β for the eikonal overlap function.

I=5-6: the parameters g_0 and γ for the Gaussian overlap function.

I=7-8: the parameters R and α for the gray disc overlap function.

I=9-10: the minimum excitation masses for projectile and target respectively.

I=11-12: the "diffractive" excitation masses for projectile and target respectively.

IOP(I): provides some statistics for the current event.

I=1: the current subcollision number.

I=2: number of Nucleon-Nucleon subcollisions.

I=3: number of projectile nucleons. For mesons this is set to 1.

I=4: number of projectile protons. For hadrons this is its charge.

I=5: as IOP(3) but for target.

I=6: as IOP(4) but for target.

I=7: the KF code for projectile. For nuclei IOP(7)=0.

I=8: as IOP(7) but for target.

I=9: number of wounded projectile nucleons.

I=10: number of wounded target nucleons.

I=11: number of projectile spectator protons.

I=12: number of target spectator protons.

I=13: number of N-N subcollisions containing at least one hard scattering.

I=14: total number hard scatterings in the event. Note IOP(14) would differ from IOP(13) only when multiple Rutherford parton scattering is allowed (KFR(7)=2).

I=15-18: used for internal flags.

NFR(I): provides some statistics for all the events in aggregate.

I=1: total number of calls to FRINGEB (the current event number).

I=2: total number of calls to FRHARDP (the number of attempts to generate Rutherford parton scattering).

I=3: total number of N-N collisions.

I=4: total number of N-N collisions containing at least one hard scattering.

I=5: total number of A-A collisions containing at least one hard scattering.

- PARAMETER (KSZ2=300)
  COMMON/FRINTN1/PPS(2,KSZ2,5),PPH(2,KSZ2,5),PPSY(2,KSZ2,5),
  PPA(2,5)

Remark: what stores here is the energy-momenta of the wounded nucleons. PPSY gives the total momentum of the system, PPS gives the soft momentum, and PPH gives the hard momentum (the total momentum of the hard scattered partons).

PPS(L,I,J): for the soft remnants,
L=1,2 - index to label the projectile (L=1) and target (L=2);
I=1,2,3,... - index to label the wounded nucleon;
J=1,2,3,4,5 - stands for P_x, P_y, P_-, P_+ and invariant mass, respectively.

PPH(L,I,J): gives the total momenta of the hard scattered partons in each nucleon. Here the index L, I and J have the same meaning as in PPS.

PPSY(L,I,J): gives the momentum for each of the nucleon systems, which is the sum of PPS(L,I,J) and PPH(L,I,J). The indices have the same meaning as in PPS.

PPA(L,J): gives momenta of the nuclei spectators.
L=1,2 - index to label the projectile spectator (L=1) and target spectator (L=2);
J=1,2,3,4,5 - stands for P_x, P_y, P_-, P_+ and mass, respectively.

- PARAMETER (KSZ2=300)
  COMMON/FRINTN2/NHP(2),IHQP(2,KSZ2),KHP(2,KSZ2,100,5),
  PHP(2,KSZ2,100,5)

Remark: this common block records the hard scattered partons in one event.

NHP(L): gives the total number of hard partons in projectile (L=1) and target nucleus (L=2).

IHQP(L,I): the total number of hard partons in the I-th wounded nucleon.
L=1,2 - index to label the projectile (L=1) and target (L=2);
I=1,2,3,... - index to label the wounded nucleon.

KHP(L,I,K,J): with the index J=1,...5, KHP duplicates the parton status codes of K(I', J) in LUJETS. The extra index L and I have the same meaning as in IHQP. K=1,2,...IHQP(L,I) labels the hard partons.

PHP(L,I,K,J): records momenta of the hard partons. With index J=1,...5 PHP duplicates the momentum matrix P(I', J) in LUJETS. Indices L, I and K have the same meaning as in KHP.

- PARAMETER (KSZ2=300)
  COMMON/FRINTN3/IDN(2,KSZ2),FMN(2,KSZ2),NUC(2,3000)

IDN(L,I), FMN(L,I): IDN stores the KF codes for nucleons, and FMN gives the corresponding masses. As usual, L=1, 2 labels a projectile or a target. I=1,2,3,... labels the nucleons in the nucleus.

NUC(L,IC): NUC(1,IC) and NUC(2,IC) give the identification numbers of the two nucleons involved in the IC-th subcollision.

Remark: FMN(L,I) can become different from the nucleon rest mass when the nucleon Fermi motion is included.

Finally there are a few common blocks taken from JETSET, PYTHIA and ARIADNE. They are used mainly for setting control parameters and transmitting relevant data. Their special usage in FRITIOF is listed below.

- COMMON/LUDAT1/MSTU(200),PARU(200),MSTJ(200),PARJ(200)
  FRITIOF shares MSTU(11) as the designated file number to which all the write out of the program is directed. It is the responsibility of the user to make this file available when writing his main program.

- COMMON/AROPTN/IAR(10), KAR(10), VAR(10)
  This common block is used to set up parameters for ARIADNE. In particular, KAR(5) and KAR(9) have been set to zero in FRITIOF, which means gluon splitting into quarks and photon radiation are forbidden in the cascading process. These effects are insignificant and ignoring them simplifies the treatment in FRITIOF.

4.3 Other subroutines

All the subroutines in FRITIOF are named with seven characters, in contrast to the functions which are named with five characters. The supporting subroutines are listed here for completeness. The purpose of each routine is briefly stated.

- SUBROUTINE FRINITA(CFRAME,CBEAM,CTARG,WIN)
  identifies the particles involved and makes initialisations. It also writes out information about the selected collision and the set up of control parameters.

- SUBROUTINE FRHILDN
  randomly orders the neutrons and protons in a nucleus, and then sets the particle codes and masses and fills out the arrays IDN and FMN in common block FRINTN3.

- SUBROUTINE FRINGEB
  administrates the generation of one event. First the routine FRANGAN is called to generate the nuclear geometry. Then FRRINGO is called to generate momentum transfers in the sequence of nucleon-nucleon subcollisions. After that, FRTORST is called, which prepares parton configurations on a string for dipole radiation. Finally LUEXEC is called for fragmentation.

- SUBROUTINE FRANGAN
  administrates the generation of nuclear collision geometry.

- SUBROUTINE FRPPCOL
  sets certain codes for hadron-hadron collisions.

- SUBROUTINE FRPACOL
  determines a set of wounded nucleons for hadron-nucleus collision.

- SUBROUTINE FRAACOL
  works out the collision geometry for nucleus-nucleus collision.

- SUBROUTINE FRNUCOR(L,NA,RMIN2,FMM,RMM,COR)
  determines the nucleon coordinates inside a nucleus (L=1 for projectile and L=2 for target) according to an appropriate nucleon density distribution.

- SUBROUTINE FRNUCOD(NA,RMIN2,A0,A2,A4,RMAX3,COR)
  determines the nucleon coordinates inside a deformed nucleus.

- SUBROUTINE FRNUCDF(NA,A0,A2,A4,RMAX3)
  calculates parameters of nucleon density distribution of a deformed nucleus.

- SUBROUTINE FRSEARC(L,fmax,xmin)
  searches for the maximum value of the nucleon density distribution and the range of the density function beyond which the nucleon density can be neglected.

- SUBROUTINE FROVLAP
  determines the parameters of the nucleon overlap function by fitting the total and inelastic cross sections.

- SUBROUTINE FRRINGO
  administrates the generation of hard partons and soft momentum transfers. It also calculates the new momenta and masses for the nucleons after the collisions.

- SUBROUTINE FRPSOFT(I,PJK,DP,DN,KFEL)
  generates the soft longitudinal momentum transfer for a N-N collision.

- SUBROUTINE FRPLIMT(DWP,DWM,DA,DB,DPLO3,DPHI3,DPLO4,DPHI4)
  returns the upper and lower limits for the phase space of the momentum transfers.

- SUBROUTINE FRCHEXG(*,I)
  administrates the comparison of the RPS with the ensuing bremsstrahlung and removes the RPS from the record if it is “drowned”.

- SUBROUTINE FRFILHD(I,IQ,KFEL)
  evaluates the mass of the nucleon system and stores information of the hard partons to common block FRINTN2.

- SUBROUTINE FRSETDM(I,KFEL,IQ)
  resets an excited nucleon state into its ground state if its mass is lower than the diffractive mass.

- SUBROUTINE FRVECTC(I, IQ, DP)
  transfers four vectors from one to another.

- SUBROUTINE FRCOLPT(PK2M,PX,PY,PX0,PY0)
  generates a soft transverse momentum exchange for N-N collision according to a Gaussian distribution.

- SUBROUTINE FRHELGE
  generates Fermi motion to all the nucleons and calculates the total momenta of the spectator nuclei.

- SUBROUTINE FRTORST(L,J)
  administrates the set up of string configurations.

- SUBROUTINE FRBELEO(IFLA,IFLB,KF)
  gives spins and quark flavours to the string ends.

- SUBROUTINE FRANGUR(L,J)
  adds a diffractive particle to the event record LUJETS.

- SUBROUTINE FRATLEO(L,J)
  sets up the string configuration and calls ARIADNE for dipole radiation.

- SUBROUTINE FRTESTG(L,IQQK,IQGL,IOK,RFA)
  compares the invariant $\mathcal{P}_T$ of the hard partons and the bremsstrahlung gluons.

- SUBROUTINE FRARIAD *(used in version 7.02 only)*
  picks out the relevant strings for dipole emission through ARIADNE.

- SUBROUTINE FRMXGPT(N1,N2,IMX,VRPTNX) *(used in version 7.02 only)*
  finds the gluons with the largest and the next largest invariant P_T.

- SUBROUTINE FRINSET(NA,N1,N2,NOK,IQ)
  inserts a hard gluon onto the string configuration.

- SUBROUTINE FRINSKK(XF,NKK)
  inserts a soft gluon kink onto the string configuration.

- SUBROUTINE FRPPART(L,PPSR,DPV1,DPV2)
  partitions the soft momentum into two parts, one for the leading quark/diquark and one for the trailing quark.

- SUBROUTINE FRSAVEN(N1,IQ)
  saves or retracts a string configuration.

- SUBROUTINE FRFILHW
  adds the colourless particles produced from parton subprocesses, such as the vector bosons or Higgs, to the event record LUJETS. This routine is not in use currently since those exotic production processes have not been included in FRITIOF.

- SUBROUTINE FRORDER(L,NS,NE)
  orders the partons according to rapidity or P_T.

- SUBROUTINE FRORD01(P,II,N,IQ)
  orders an array in a ascending or descending manner.

- SUBROUTINE FRQPROB(KFI,KFT,IQ)
  evaluates various scattering cross sections.

- SUBROUTINE FRHARDP(KFI,KFT,W,IHAV,IQ)
  generates hard scattering by calling PYTHIA.

- SUBROUTINE FRSETPY(IQ)
  sets control parameters for PYTHIA.

- SUBROUTINE FRVECRC(JF,L,IQ)
  converts four vectors from one array into another.

- SUBROUTINE FREDIPY
  picks out the outgoing hard partons from the event record of PYTHIA.

- SUBROUTINE FRHPLIS
  outputs the PYTHIA event record and the hard partons picked out by FREDIPY. This routine is called only when error occurs and there seems to be a need to visually examine the hard scattering event.

- SUBROUTINE FRGAUSS(P,V,PMAX)
  generates a value for P according to a Gaussian distribution with the average $< P^2 >= V$. The Gaussian is cut off at PMAX.

- SUBROUTINE FRBETAV(ID,DBETA,DP)
  calculates the beta factor for boosting a pair of momenta into their centre-of-momentum frame.

- SUBROUTINE FRTOCMS(ID,IQ,DP,DBETAO)
  boosts two momenta into their centre-of-momentum frame, or do the reverse.

- SUBROUTINE FRPOLAR(DTHE,DPHI,DP)
  returns the polar angles about which a system needs to be rotated in order to put a four vector on the z-axis.

- SUBROUTINE FRROTAR(DTHE,DPHI,IQ,DP)
  rotates a pair of momenta by the polar angles DTHE and DPHI.

- SUBROUTINE FRROTAY(DTHE,DPV)
  rotates coordinates around the y-axis by an angle DTHE.

- SUBROUTINE FRROTAZ(DPHI,DPV)
  rotates coordinates around the z-axis by an angle DPHI.

- SUBROUTINE FRBOOT1(ID,DPV,DBETA)
  boosts a single four vector DPV(4) by a beta factor DBETA(3).

- SUBROUTINE FRMGOUT(ID,ILIST,MESG,A,B,C,D,E)
  manages the writing out of error messages.

- SUBROUTINE FRVALUE(IQ)
  writes out the values of the FRITIOF parameters. For IQ=0, the output is written in file MSTU(11), otherwise the output will be written in a file called 'Oxchk'.
- SUBROUTINE FRPYINI(FRAME,BEAM,TARGET,WIN)
- SUBROUTINE FRPYXTO
  These two routines are taken from PYTHIA with modifications made to accommodate a different Block and Cahn parametrization and some different handling in meson-nucleon cross sections.
- SUBROUTINE FRUPCAS(STR) converts a character string to uppercase.

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Appendix A A Sample Main Program

```
C..This program generates a few sample FRITIOF events, and then does
C..histogram for negatively charged particle multiplicity distribution
C..in O+Au collision at 200 GeV/nucleon lab energy.
C..One does not usually need to mix different types of events,
C..the purpose here is only for illustrating the possible usages.
C..This routine, loaded together with (FRITIOF_7.02, ARIADNE_4.02r,
C..PYTHIA_5.5 and JETSET_7.3) can be used to test the installation of Fritiof.
C-----------------------------------------------------------------------

      PARAMETER (KSZJ=4000,KSZ1=20)
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 10 events (of course a lot more events are needed realistically):
      NEVENT=10
      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
```

References

[1] B. Nilsson-Almqvist and E. Stenlund, *Comut. Phys. Commun.* **43** (1987) 387.

[2] B. Andersson, G. Gustafson and B. Nilsson-Almqvist, *Nucl. Phys.* **Vol. 34** (1986) 451.

[3] B. Andersson, S. Garpman, H.-Å. Gustavsson, G. Gustafson and B. Nilsson-Almqvist, I. Otterlund and E. Stenlund, *Phys. Scripta* **B281** (1987) 289.

[4] G. Gustafson, *Phys. Lett.* **175B** (1986) 453.

[5] B. Andersson, G. Gustafson, G. Ingelman and T. Sjöstrand, *Phys. Rep.* **97** (1983) 31.

[6] C. Albajar, *et al.*, *Nucl. Phys.* **B309** (1988) 405.

[7] T. Sjöstrand and M. van Zijl, *Phys. Rev.* **D36** (1987) 2019.

[8] H.-U. Bengtsson and T. Sjöstrand, *Comput. Phys. Commun.* **46** (1987) 43
An updated version of this paper, "A Manual to The Lund Monte Carlo for Hadronic Processes: PYTHIA version 5.5", is available upon request to the authors.

[9] L. Lönnblad, "`ARIADNE-3`, A Monte Carlo for QCD Cascades in the Colour Dipole Formulation", Lund preprint LU TP 89-10.

[10] L. Lönnblad, "`ARIADNE Version 4`", preprint DESY 92-046.

[11] B. Andersson, G. Gustafson, L. Lönnblad and U. Petterson, *Z. Phys.* **C43** (1989) 625.

[12] L. Ding and E. Stenlund, "A Monte Carlo for Nuclear Collision Geometry", Lund preprint LU TP 89-6.

[13] B. Andersson, G. Gustafson and B. Nilsson-Almqvist, "A High Energy String Dynamics Model for Hadronic Interactions", Lund preprint LU TP 87-6.

[14] B. Andersson, G. Gustafson and H. Pi, in preparation.

[15] T. Sjöstrand, "A Manual to The Lund Monte Carlo for Jet Fragmentation and e^+e^- Physics: JETSET version 7.3", available upon request to the author.

[16] R. C. Barrett and D. F. Jackson, *Nuclear Sizes and Structure* (Oxford University, New York, 1977).

[17] M. M. Block and R. N. Cahn, in *Physics Simulations at High Energy*, edited by V. Barger, T. Gottschalk and F. Halzen (World Scientific, Singapore, 1987), p. 89.

[18] Particle Data Group,
Review of Particle Properties, *Phys. Lett.* **B239** (1990) 1.
Refer to section III.67 for the particle codes.

[19] M. Z. Akrawy *et al*, *Z. Phys.* **C47** (1990) 505.