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# DTUNUC

# Sampling of hadron-nucleus and nucleus-nucleus interactions according to the dual parton model

## VERSION 1.00

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**Abstract**

The dual parton model provides a unique picture not only for hadron–hadron interactions, but also for the description of particle production in hadron–nucleus and nucleus–nucleus collisions at high energies. Within this model the high–energy projectile undergoes a multiple scattering process as formulated in Glauber's approach; particle production is realized by the fragmentation of colorless parton–parton chains constructed from the quark content of the interacting hadrons/nucleons. The actual version of our Monte Carlo realization of the model includes the cascading of secondaries within the target as well as in the projectile which is suppressed by the formation time concept. Semihard parton–parton collisions (for the description of minijet production) are not included in this version. With this restriction the model should not be applied beyond RHIC energies ($\sqrt{s} \simeq 200\ GeV$, $E_{lab} \simeq 20\ TeV$).
At lab energies below 5 $GeV$ hadron–nucleus collisions are described within the conventional intranuclear cascade picture; thus the model may be applied in the range well below 1 $GeV$.

# 1 Program Summary

| | |
|---|---|
| Title of the program: | DTUNUC |
| Computer: | IBM–3090, CRAY, IBM–RISC/6000, VAX |
| Program language: | FORTRAN-77 |
| Number of program lines: | about 17,000 |
| Other programs called: (included in DTUNUC in modified form) | DIAGEN [1]<br>Sampling of configurations for nucleus-nucleus interactions within the Glauber formalism<br>RNDM()<br>Random number generator taken from ref. [2].<br>BAMJET [3]<br>Sampling the hadronization of strings.<br>DECAY [4]<br>Sampling the decay of hadron resonances.<br>HADRIN [5]<br>Sampling hadron-nucleon interactions below 5 GeV. |
| Method of solution: | Monte Carlo event generator. |

# 2 Basic physical concepts of the model

The first successfull applications of the Monte Carlo version of the dual parton model (DPM) to hadron–nucleus [7] and nucleus–nucleus [8, 9] collisions also demonstrated that the cascade of created secondaries in the target (and projectile) nuclei contributes significantly to particle production in the target (and projectile) fragmentation regions. On the other hand, it is known for many years that a naive treatment of intranuclear cascade processes on the basis of elementary cross sections overestimates the particle yields, if the incident energy significantly exceeds five or ten GeV [11].
This problem may be solved by introducing the concept of a formation zone [13, 14] suppressing in a natural way the cascading of high–energy secondaries. The actual Monte Carlo model implemented as DTUNUC 1.00 includes intranuclear cascade processes of the created secondaries combined with the formation time concept.
In the following we briefly sketch the basic ideas of the model and mention the most important ingredients; for a more detailed description of the model as applied in the code we refer to Refs. [7, 15, 16].

## 2.1 The Monte Carlo realization of the dual parton model for hadron-nucleus and nucleus-nucleus collisions above 5 GeV

The model starts from the impulse approximation for the interacting nuclei – i.e. with a frozen discrete spatial distribution of nucleons sampled from standard density distributions [1]. The primary interaction of the incident high–energy projectile proceeds via totally $n$ elementary collisions between $n_p$ and $n_t$ nucleons from the projectile (for incident hadrons $n_p = 1$ ) and the target nuclei, resp. Actual numbers $n, n_p$ and $n_t$ are sampled on the basis of Glauber's multiple scattering formalism using the Monte Carlo algorithm of Ref.[1]. Note that individual hadrons may undergo several interactions. Particle production in each elementary collision is descibed by the fragmentation of two color–neutral parton–parton chains. Those chains are constructed from the valence quark systems or – in the case of repeated scatterings of single hadrons – from sea–$q\bar{q}$ pairs of the interacting hadrons. The hadronization of single chains is handled by the Monte Carlo codes BAMJET [3] and DECAY [4] (both the codes have been modified for a convenient application in DTUNUC).

## 2.2 Realization of the intranuclear cascade process

As a realization of the formation zone concept an actual formation time is sampled from an exponential distribution for all the secondaries from the primary high–energy collision [15, 16]. For the characteristic formation time of a secondary $s$ (defined in its rest frame) both a $p_\perp$–dependent expression [14, 10],

$$\tau_s = \tau_0 \frac{m_s^2}{m_s^2 + p_{\perp s}^2}, \tag{1}$$

as well as a constant value $\tau_0$ might be considered, where $\tau_0$ is treated as free parameter. Published results [16, 17] have been obtained with the $p_\perp$–dependent version.
Secondaries are followed along straight trajectories and may induce intranuclear cascade processes if they 'materialize' inside either the target or the projectile nuclei; otherwise they leave the nucleus without interaction. Below 9 GeV inelastic secondary interactions are described by the Monte Carlo code HADRIN [5]. For the sampling of elastic nucleon–nucleon scattering below 4 $GeV$ the parametrization of the HETC-KFA code [6] was adopted; at higher energies and for all other particle species the parametrization

$$\frac{d\sigma}{dt} \propto \exp(-at), \qquad a = 10\ GeV^{-2}$$

is applied. Reinteractions of energetic secondaries beyond 9 GeV within the colliding nuclei are very rare and, therefore, neglected in this model version.
Fermi momenta for nucleons as well as a simplified treatment of the nuclear potential and the Pauli principle are introduced to control the generation of low-energy particles (protons and neutrons mainly) [16]. Nucleon momenta are sampled from zero-temperature Fermi distributions

$$\frac{dN^{n,p}}{dp} = N^{n,p}\frac{3p^2}{(p_F^{n,p})^3}. \tag{2}$$

The maximum allowed Fermi momenta of neutrons and protons are

$$p_F^{n,p} = \left[\left(\frac{N^{n,p}}{V_A}\right)\frac{3h^3}{8\pi}\right]^{\frac{1}{3}} \simeq 0.4\,(\rho_A^{n,p})^{\frac{1}{3}}\ GeV/c, \tag{3}$$

where $V_A$ denotes the volume of the corresponding nucleus, calculated for an approximate nuclear radius $R_A = r_0 A^{\frac{1}{3}}$ ($r_0 \sim 1fm$); $\rho_A^{n,p}$ is the average density of protons and neutrons, resp., within the nucleus.
Modifications of the actual nucleon momentum distribution as discussed in some classical intranuclear cascade models [12, 11] effectively result in a reduction of the Fermi momenta as compared to those sampled from Eq. (3). This effect can be estimated by a correction factor which modifies the sampled Fermi momenta:

$$p_{act}^{nucleon} = \alpha_{mod}^F \cdot p_{samp}^{nucleon}.$$

Published results have been obtained with $\alpha_{mod}^F = 0.6$.
The depth of the nuclear potential is defined by the Fermi energy and a typical binding energy for outer shell nucleons,

$$V^{n,p} = \frac{(p_F^{n,p})^2}{2m_{n,p}} + \bar{E}_{bind}; \tag{4}$$

$\bar{E}_{bind}$ is estimated from a simple phenomenological mass formula. Coulomb effects as well as the absorption of stopped negative mesons are treated in a rough approximation.

## 2.3 Hadron–nucleus interactions below 5 $GeV$

For theoretical as well as technical reasons (kinematics) the application of the parton model for the description of the primary inelastic interaction is limited to not too low energies well above 1 GeV. Therefore, the conventional intranuclear cascade picture is used for lab energies below 5 GeV: The projectile hadron collides with a single nucleon inside the target nucleus, created secondaries may induce cascading. Inelastic as well as elastic hadron–nucleon interactions are described in the same way as mentioned in the previous subsection. The extrapolation to nucleus–nucleus interactions below 5 GeV has not been coded so far.

## 2.4 Restrictions of the actual program version

So far this program version DTUNUC 1.00 has been applied mainly for hadron–nucleus and central nucleus–nucleus collisions. The application to minimum bias nucleus–nucleus collisions is not yet fully tested (in particular, this concerns the cascade in the projectile nucleus).
At ultrahigh energies minijet production [18] as well as interactions of created secondaries with each other are estimated to contribute significantly to particle production processes. Both these features will only be included in the versions 2.xx of the model. Therefore, the application of the model versions 1.xx to hadron–nucleus and nucleus–nucleus collisions beyond RHIC energies, i.e. $\sqrt{s} \simeq 200\ GeV$ and $E_{lab} \simeq 20\ TeV$, resp., is not recommended. The appropriate treatment of diffraction is another problem which is presently under study and will be included in a later release. Diffractive phenomena will somewhat affect multiplicity and rapidity distributions in minimum bias events.
Finally, version 1.00 of DTUNUC works for hadron–nucleus collisions above 50 MeV kinetic energy and nucleus–nucleus interactions above 5 GeV.

# 3 Description of the program DTUNUC

The basic event generating unit of the code is the subroutine KKINC. Each call of this routine samples one inelastic hadron–nucleus or nucleus–nucleus interaction. Use and necessary initializations are described first in this section; a test program provided with the program package demonstrates the potential application. In the following subsection we discuss important model parameters and define their location in the code for potential user access. The basic structure of the supplied code is described in further subsections.

## 3.1 The event generator KKINC and its initialization

As already mentioned the code DTUNUC uses several other programs. The initialization of the **BAMJET**[3], **DECAY**[4] and **HADRIN**[5] codes requires *one single call* of the subroutines DPRIBL, DDATAR, DCHANT, DCHANH and DHADDE. The subroutine DPRIBL reads data on particle properties and decay channels of resonances from the file 'BBLO.DAT'.
Further initializations and parameter definitions are provided via the named BLOCK DATA BLKDT1 and the subroutine DEFAUL(EPN,PPN). The routine DEFAUL has to be called before event generation, too. Besides other initializations this routine sets the parameters, characterizing the type of the actual interaction, for $\pi^+Cu$ collisions at 200 GeV; EPN and PPN (output variables) give energy and momentum in the lab–system. Actual predefinition and locations of those parameters which might be changed potentially by the user are discussed in the following subsection.
Basic information for the application of the Glauber formalism according to the code **DIAGEN**[1] is generated by by the subroutine

SHMAKI (IP, IPZ, IT, ITZ, RPROJ, RTARG, PPN)

which requires the following input parameters defining the actual interaction:

**IP, IPZ:** nucleon number/atomic number of the projectile nucleus; set IP=IPZ=1 for incident hadrons;

**IT, ITZ:** nucleon number/atomic number of the target nucleus;

**PN:** projectile momentum in GeV/c (per nucleon)

Since the calculations performed by SHMAKI are time consuming, in particular for heavy target nuclei, and in general have to be repeated for each different reaction type and energy, resp., the test program provided offers an option to prepare a data file 'GLAUBTAR.DAT' containing the necessary information for hadron–nucleus interactions to be considered. This file may be generated in a separate run of the test program using the option 'GLAUBERI', compare Appendix A. The information from this file is read for a given target nucleus (IT, ITZ) by means of a subroutine call

CALL SHMAKF(IP,IPZ,IT,ITZ)

(with IP=IPZ=1.). For the use of different materials in one calculation SHMAKF has to be called subsequently with the corresponding parameters (IT,ITZ). The information read from the file 'GLAUBTAR.DAT' is numbered internally by the index KKMAT=1,2,...

according to the sequence of SHMAKF calls; up to 50 materials may be stored in the standard version of the program. If a larger number of materials is to be used the corresponding dimension in the common /DTUMAT/ has to be increased. (If the required data are not found in the file 'GLAUBTAR.DAT' the execution is stopped.)
After these initializations each call of the subroutine

KKINC (EPN, IT, ITZ, IP, IPZ, IPROJ, KKMAT)

generates a single event. The input parameters not yet described have the following meaning:

**IPROJ:** projectile type for hadron–nucleus collisions;
DTUNUC uses naming and numbering conventions of the FLUKA code which are listed for stable hadrons in Table 2 of Appendix A.1;

**KKMAT:** controls the access of the event generator to the information on the Glauber formalism:
KKMAT=0 : Glauber data expected from SHMAKI calculation;
KKMAT>0 : Glauber data expected from the KKMAT'th call of the subroutine SHMAKF.

The following commands will cause the generator to sample one inelastic $\pi^+Cu$ event at 200 GeV laboratory energy:

```
*** BAMJET and DECAY initialization
      CALL DPRIBL
      CALL DDATAR
      CALL DCHANT
*** HADRIN initialization
      CALL DHADDE
      CALL DCHANH
*** initialization of the random number generator supplied with DTUNUC
      CALL RNDMST(12,34,56,78)
*** initialization of DTUNUC parameters (output: EPN=200 GeV)
      CALL DEFAUL(EPN,PPN)
*** initialization for the Glauber formalism by explicit calculation
*** for the actual reaction (projectile/target/energy = pi+/Cu/200 GeV)
      IP=1
      IPZ=1
      IT=64
      ITZ=29
      CALL SHMAKI(IP,IPZ,IT,ITZ,RPROJ,RTARG,PPN)
*** sampling of 1 event (pi+ has type IPROJ=13)
      IPROJ=13
      KKMAT=0
      CALL KKINC(EPN,IT,ITZ,IP,IPZ,IPROJ,KKMAT)}
      STOP
```

To use the information from the file 'GLAUBTAR.DAT' one has to call SHMAKF instead of SHMAKI and define KKMAT=1.

## 3.2 Information on the final state particles

During the generation of single events several entries are scored in the common block /HKKEVT/ characterizing subsequent stages of the sampling process: Information on initial state nucleons as well as on interacting partons and constructed parton chains, decaying resonances and final state particles is stored into this common block. It has the following structure, completely defined in Appendix B:

```
PARAMETER (NMXHKK=.....)
        COMMON /HKKEVT/ NHKK,NEVHKK,ISTHKK(NMXHKK),IDHKK(NMXHKK),
       &                JMOHKK(2,NMXHKK),JDAHKK(2,NMXHKK),
       &                PHKK(5,NMXHKK),VHKK(4,NMXHKK),WHKK(4,NMXHKK)
```

The entries are characterized by their status ISTHKK and type IDHKK as well as by the 4-momenta PHKK; additional pointers define 'parents' and 'daughters' of the actual entry. Final state particles are identified by their status ISTHKK(.)=1.
The structure of this common block closely follows the suggestions of Ref. [19]; conventions for the description of the event history are described in some detail in Appendix B.2, followed by a sample event in Appendix B.3.
The information on the residual nucleus (in case of hadron–nucleus interactions) is to be extracted from the common block

```
        COMMON /TNUCFI/ AMTFIN,AMFINO,EEXCTA,PTFINX,PTFINY,PTFINZ,PTFINE,
       +                ITFIN,ITZFIN,NNTAR,NPTAR,NHTAR,NQTAR,NPARF
```

with the following notations:

**AMTFIN:** invariant mass of the residual target nucleus;

**AMFINO:** approximate ground state mass of the residual target nucleus;

**EEXCTA:** excitation energy of the residual target nucleus;

**PTFINX/Y/Z/E:** 4–momentum of the residual target nucleus;

**ITFIN:** total baryon number and

**ITZFIN:** number of positive baryons within the residual nucleus.

These quantities are determined in the subroutine FINALE (code module DMNUC1).

## 3.3 Important parameters of the code

In this subsection we summarize physical meaning and location of those parameters which may have a significant influence on observable quantities.

### 3.3.1 Sampling of x–values for partons

Parton x–values for a given hadron are sampled from distributions of the general form

$$q(x) \propto x^{-\alpha}(1-x)^{\beta},$$

subject to the reqirement that their sum is equal to one. The user has access to the $\beta$–parameters for valence quarks which have, however, only minor influence on the final results. They are set to the following default values:

$$\beta_v^{nuc} = 2.0, \qquad \beta_v^{mes} = 1.5;$$

for reasons of an optimal sampling efficiency $\beta_{sea} \equiv 0.0$. From standard Regge arguments the power in x is fixed to be $\alpha^{sea} = 1.0$ and $\alpha^{val} = 0.5$ for sea and valence quarks, resp.; these values may not be changed by the user.
Additionally, the x–values for partons of colliding projectile and target hadrons are correlated by the interaction mechanism within the DTU model: The constructed color–neutral parton–parton systems (chains) should aquire at least some minimum mass $M_{min}$ to allow the fragmentation into final state hadrons,

$$M^2 \simeq x^{target} \cdot x^{project.} \cdot s \geq M_{min}^2;$$

otherwise the collision numbers sampled according to the Glauber formalism may be strongly biased. Therefore, lower cuts are defined for the sampling of x–values, $x^{min} = C/\sqrt{s}$, differing for valence quarks, diquarks and sea quarks, resp. To ensure minimum chain masses for valence–valence (v–v) systems the following values are set by default within DTUNUC:

$$C_q^{val} = 1.0, \qquad C_{qq}^{val} = 2.0, \qquad C_{q/\bar{q}}^{sea} = 0.2$$

However, since these cuts are imposed for both the projectile and the target independently, lower (but still kinematically allowed) chain masses tend to be suppressed at least for v–v systems. This unwanted effect is partly corrected by resampling the x–value of the valence quark with the lowest kinematically allowed $x_v^{min}$ if the mass of a v–v chain exceeds a certain value $M_{vv}^{thr}$. In a similar way the mass of sea–sea (s–s) systems may be required to exceed some minimum value,

$$M_{ss} \geq M_{ss}^{min}.$$

(Note that the s–s chains are only formed in nucleus–nucleus collisions.) The default values for the last mentioned parameters are

$$M_{vv}^{thr} = 6 \text{ GeV}, \qquad M_{ss}^{min} = 0.14 \text{ GeV}.$$

All the user accessible parameters discussed so far are located in the common block

```
      COMMON /XSEADI/ XSEACU,UNON,UNOM,UNOSEA, CVQ,CDQ,CSEA,SSMIMA,
     +                SSMIMQ,VVMTHR
```

with the following assignments:

| | | |
|---|---|---|
| $\beta_v^{nuc}$ = UNON | $\beta_v^{mes}$ = UNOM | |
| $C_q^{val}$ = CVQ | $C_{qq}^{val}$ = CDQ | $C_{q/\bar{q}}^{sea}$ = CSEA |
| $M_{ss}^{min}$ = SSMIMA | $(M_{ss}^{min})^2$ = SSMIMQ | $M_{vv}^{thr}$ = VVMTHR |

### 3.3.2 Generation of transverse momenta for secondary hadrons

In the model there are two sources of transverse momenta for created secondaries. First the partons aquire an internal $p_\perp$ which is taken into account in the construction of parton–parton chains. The subsequent hadronization of the partonic chains is modelled by the BAMJET code [3] which itself assignes to the created particles transverse momenta with respect to the jet axis.
Internal transverse momenta for partons are sampled within the subroutine SELPT (file DMNUC3) according to the following distribution for the reduced transverse energy $E_s = E_\perp - m_p$,

$$\frac{dn}{dE_s} \propto E_s \exp\left(-\gamma^2 E_s/2\right) \tag{5}$$

with

$$p_\perp = \sqrt{E_s^2 + 2E_s m_p}, \qquad m_p = 0.94 \text{ GeV},$$

where the slope parameter $\gamma \equiv$ BB3 is defined directly in this routine (default value BB3=6.0). However, in the case of severe kinematical limitations for individual partons/chains this parameter may be modified in the sampling process.
The internal parameters of the BAMJET code have been adjusted to obtain a reasonable description of pp collisons and should not be modified by users.

### 3.3.3 Intranuclear cascade

There are two important parameters controlling the development of the intranuclear cascade which have been defined in the previous section: The formation time $\tau_0$ of created secondary hadrons, and the factor $\alpha^F_{mod}$ scaling the Fermi momenta of nucleons. With increasing $\tau_0$ the number of cascade generations and the number of low-energy particles will be reduced; $\alpha^F_{mod}$ provides the possibility for a certain modification of the momentum distribution for low–energy nucleons.
Additionally, the maximum number of cascade generations KTAUGE (by default 25) may be reset by the user to estimate the influence of the intranuclear cascade. In particular, the cascade is switched off by the choice KTAUGE=0.
In the code the corresponding parameters are defined in the common blocks

```
      COMMON /TAUFO/  TAUFOR,KTAUGE,ITAUVE
      COMMON /NUCIMP/ PRMOM(5,248),TAMOM(5,248),...,
     +                PREBIN,TAEBIN,FERMOD,ETACOU
```

where $\tau_0 \equiv$ TAUFOR and $\alpha^F_{mod} \equiv$ FERMOD. The option ITAUVE determines whether the $p_\perp$–dependent definition of the formation time (ITAUVE=1) or the constant value $\tau_0$ (ITAUVE=2) are used; by default ITAUVE=1 (compare Section 2.2).

## 3.4 Structure of the supplied code

The DTUNUC standard source code is stored in several FORTRAN files, listed in the following:

- DMNUC1, DMNUC2, DMNUC3

  These modules contain all subroutines needed to describe the primary interaction according to the DPM as defined in the previous section. This includes the assignment of Fermi momenta to nucleons, construction of chains and monitoring their decay as well as the intranuclear cascade for generated secondaries.

- DMTCBSHM

  Contains the BAMJET [3] and DECAY [4] routines for chain fragmentation, routines to test and call BAMJET as well as the routines from DIAGEN [1] for sampling the actual numbers of elementary collisions (i.e. $n, n_p, n_t$) according to the Glauber formalism.

- DMHADRIN

  Includes the HADRIN [5] routines for event generation in hadron-nucleon collisions below 5 $GeV$ as well as routines for the calculation of energy and reaction dependent cross sections.

- DMNULIB

  Contains few standard routines usually uneffected by further developments of the code, including the applied random number generator [2].

- DMTEST

  Contains the test program mentioned in the beginning of this subsection as well as a sample histogram routine producing line printer output for average multiplicities, rapidity and pseudorapidity distributions for generated particles.

- BBLO.DAT

  ASCII data file to be read by the subroutine DPRIBL for initialization of the HADRIN, BAMJET and DECAY codes.

## 3.5 Sequence of subroutine calls for event generation

1. The generator subroutine KKINC monitors the sampling of a single event by one call of KKEVT, repeated FOZOKL calls and call(s) of the subroutine FINALE.

2. The subroutine KKEVT performs the sampling of the primary projectile–target interaction. This includes

   - sampling of the actual nucleon coordinates and assignment of 'partners' in the $n$ elementary interactions between $n_p$ and $n_t$ nucleons from the projectile and the target, resp., done in SHMAKO [1];
   - sampling of Fermi momenta of all nucleons in colliding nuclei in FER4M;
   - sampling of x-values for the appropriate quark systems (quarks, antiquarks and diquarks, resp.) from the interacting hadrons in the subroutine XKSAMP and assignment of quark flavors in FLKSAM;
   - construction of color neutral parton-parton chains in the subroutines KKEVVV, KKEVSV, KKEVVS, KKEVSS;
   - hadronization of chains via the BAMJET and DECAY codes monitored by the subroutine HADRKK;

   finally KKEVT returns the control to KKINC.

3. The intranuclear cascade is modeled by subsequent calls of FOZOKL for each secondary which did not leave the interacting nuclei. FOZOKL transports the particle either until the next interaction or until it leaves the nucleus.

4. Within the subroutine FINALE the properties of the final state nucleus are calculated from energy–momentum conservation and the conservation of additive quantum numbers.

## 3.6 The test program DMTEST

The event generator itself is supplied together with a test program which may serve as an example for the application of the program. By a call of the subroutine DMINIT (included in the source file DMNUC1) the main program DMTEST does the necessary initializations discussed above. It also allows the definition/modification of model parameters via input options explained in Appendix A.
The sample histogram routine DISTR (source file DMTEST) generates line printer output for average multiplicities, rapidity and pseudorapidity distributions for created particles. The scoring procedure demonstrates how the information on the event history stored in the common /HKKEVT/ may be applied to extract the properties of the final state particles.

## 3.7 Remarks on the other codes applied in DTUNUC: DIAGEN, BAMJET, DECAY, HADRIN and RNDM

All the external codes applied are well documented. The generator DIAGEN [1] samples configurations for nucleus-nucleus interactions in the framework of the Glauber model, i.e. spatial coordinates of nucleons in projectile and target nuclei, resp., as well as the actual numbers of 'elementary' interactions $n$, $n_p$ and $n_t$ (comp. sect. 2). DIAGEN routines are called via SHMAKI (initialization) and SHMAKO (sampling of configurations), both included in the file DMTCBSHM.
Basic data for the initialization of the chain fragmentation model BAMJET [3] and the resonance decay routine DECAY [4] are read by the subroutine DPRIBL from the file BBLO.DAT to be assigned to the logical unit 11. DTUNUC calls BAMJET via routines which already perform Lorentz transformations and rotations of the events generated in BAMJET. The actual calling sequence is HADJET–CALBAM–DBAMJE; HADJET is called from the HADRxx routines (module DMNUC3) monitoring the hadronization of parton chains.
A modified version of the resonance decay routine is defined by the subroutine DECHKK treating the decay of resonances from the common /HKKEVT/.
The program HADRIN [5] for the description of hadron-nucleon interactions below 5 $GeV$ is well tested against data [20]. In DTUNUC it is called via the subroutine FHAD (file DMHADRIN).
The algorithm applied for the generation of uniform random numbers (function RNDM) has been taken from ref. [2]. The generated sequence of pseudorandom numbers should be independent of the actual hardware (if a real number has at least 24 significant bits in the internal representation). This generator has a period of about $2^{144}$. A few more comments and a test routine are provided in the source file DMNULIB.

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# Appendix A :
# The test program DMTEST

The test program demonstrates the application of the event generating routine KKINC and the extraction of information on the produced secondaries from the common block /HKKEVT/ (in the routine DISTR). Furthermore, it allows a simple redefinition of some important model parameters. It may also be used to prepare data files containing reaction specific information needed for the application of the Glauber formalism. In the case of event generation few standard histograms are constructed from sampled events.
All program activities are monitored by input options. Each input option is identified by a code word and either changes the default values of variables and/or demands some action. Tab. 1 summarizes the standard input options. All variables read from the input file have default values.

Table 1: Options read by the subroutine DMINIT

| Option | Description |
|---|---|
| TITLE | next card is the run title |
| COMMENT | adds comments to the input data stream |
| PROJPAR | definition of the projectile |
| TARPAR | definition of the target |
| GLAUBERI | initialization of the Glauber formalism for hadron–nucleus interactions / data are written on unit 47 |
| ENERGY | beam energy ($GeV$; per nucleon for nuclei) |
| MOMENTUM | beam momentum ($GeV/c$; per nucleon for nuclei) |
| CENTRAL | central A-A collisions forced |
| TAUFOR | definition of the formation time parameter |
| SEADISTR | monitors the x-behaviour of the quark distributions |
| XCUTS | monitors cuts for x–sampling |
| FERMI | monitors assignment of Fermi momenta to nucleons |
| START | start event sampling |
| STOP | stop the run |
| PARTICLE | print table of available particles and properties |

## A.1: Description of input options

All input records of DTUNUC have the following form:

```
CODEWD, (WHAT(I), I = 1,6), SDUM
FORMAT (A8, 2X, 6E 10.0, A8)
```

In the following we describe the meaning of the corresponding variables for the standard input options in the same order as the code words CODEWD are listed in Tab. 1.

- Code word = 'TITLE'

  This option card must be followed by a card giving a run title, which will be reproduced in the output.

- Code word = 'COMMENT'

  This option allows to add comments to the input file at arbitrary positions.

  **WHAT(1):** number of comment cards following this card.
  default : 1.0

- Code word = 'PROJPAR'

  This card defines the type of the projectile;
  if given it has to be included <u>before</u> the MOMENTUM/ENERGY option(s).

  **SDUM:** defines the projectile to be a hadron if given; for naming conventions see Table 2.
  If SDUM is given WHAT(1) and WHAT(2) need no specification; for projectile nuclei SDUM has no meaning.

  **WHAT(1):** mass number of projectile nucleus - IP

  **WHAT(2):** atomic number of projectile nucleus - IPZ

  default: incident $\pi^+$.

- Code word = 'TARPAR'

  This card defines the type of the target nucleus.

  **WHAT(1):** mass number of projectile nucleus - IP

  **WHAT(2):** atomic number of projectile nucleus - IPZ

  default: $Cu$ target ( IP=64, IPZ=29 )

Table 2: Naming conventions for projectile hadrons to be used for the SDUM parameter of the PROJPAR input card

| 'SDUM' | Particle |
|---|---|
| PROTON | $p$ |
| APROTON | $\bar{p}$ |
| NEUTRON | $n$ |
| ANEUTRON | $\bar{n}$ |
| KAONLONG | $K_L^0$ |
| PION+ | $\pi^+$ |
| PION- | $\pi^-$ |
| KAON+ | $K^+$ |
| KAON- | $K^-$ |
| LAMBDA | $\Lambda$ |
| ALAMBDA | $\bar{\Lambda}$ |
| KAONSHRT | $K_S^0$ |
| SIGMA- | $\Sigma^-$ |
| SIGMA+ | $\Sigma^+$ |
| SIGMAZER | $\Sigma^0$ |
| PIZERO | $\pi^0$ |
| KAONZERO | $K^0$ |
| AKAONZER | $\bar{K}^0$ |

- Code word = 'GLAUBERI'

  Requests the initialization of the Glauber formalism for hadron–nucleus interactions;
  the target nucleus has to be defined by the code word TARPAR in advance;
  tables of impact parameter distributions for b–sampling are written to unit 47 for several momenta ($p_{lab} = \sqrt{10}^{(i+1)}; i = 1, ..., 10$) and different projectiles ($p, \pi^+$);
  WHAT parameters have no meaning.

- Code word = 'ENERGY'

  This card defines the energy of the projectile in the target rest system. For incident nuclei the energy per nucleon is expected.
  NOTE: only one of the ENERGY and the MOMENTUM options is necessary, the last defined option is applied; both these options are to be given after the PROJPAR definition.

  **WHAT(1):** projectile energy in $GeV$

  **WHAT(1):** projectile energy in $GeV$
  default: 200 $GeV$

- Code word = 'MOMENTUM'

  This card defines the momentum of the projectile in the target rest system. For incident nuclei the momentum per nucleon is expected.

  **WHAT(1):** projectile momentum in $GeV/c$; default: 200 $GeV/c$

  **NOTE:** ENERGY and/or MOMENTUM options are to be given before the PROJPAR definition.

- Code word = 'CENTRAL'

  This code word forces central nucleus-nucleus collisions, i.e. most nucleons of the projectile nucleus are forced to interact. The actual requirement depends on the atomic number of both the projectile and the target nuclei and is defined in the subroutine KKEVT (source file DMNUC2, after CALL SHMAKO). Furthermore, the actual impact parameter is set to zero for this case in subroutine MODB (source file DMTCBSHM).

  **WHAT(1):** central collisions forced for WHAT(1)= 1.0;
  default: 0.0, i.e. no forcing.

- Code word = 'TAUFOR'

  This option defines the formation time parameter controlling the intranuclear cascade. Additionally it allows to restrict the number of generations of secondary cascade interactions.

  **WHAT(1):** formation time in $fm/c$; default: 5 $fm/c$

  **WHAT(2):** maximum number of allowed generations of secondary interactions; default: 25

  **WHAT(3):** monitors the definition of the formation time actually applied (comp. Subsects. 2.3 and 3.3.3):
  WHAT(3)=1 : $p_\perp$–dependent formation time,
  WHAT(3)=2 : constant formation time

- Code word = 'SEADISTR'

  This option card defines properties of the quark distributions, which are of the general form $q(x) \propto x^{-\alpha}(1-x)^{\beta}$.

  **WHAT(1):** $\alpha^{sea}$ for sea-quark distributions ($\alpha \leq 1.0$);
  default : $\alpha^{sea} = 1.0$

  **WHAT(2):** $\beta^{nuc}$ for valence-quark distributions of nucleons;
  default : $\beta^{nuc} = 2.0$

  **WHAT(3):** $\beta^{mes}$ for valence-quark distributions of mesons;
  default : $\beta^{mes} = 1.5$

  **WHAT(4):** $\beta^{sea}$ for sea-quark distributions;
  default : $\beta^{sea} = 5.0$

  NOTE: for reasons of the sampling efficiency the parameters for the sea distribution are fixed to $\alpha^{sea} = 1.0$ and $\beta^{sea} = 0.0$ in the present version of the subroutine XKSAMP and cannot be changed easily by the user.

- Code word = 'XCUTS'

  This option redefines the lower cuts for the sampling of x-values to ensure minimum chain masses for hadronization (used in XKSAMP).

  **WHAT(1)** = CVQ ; $(x_q^{val})^{min} = \mathrm{CVQ}/\sqrt{s}$,
  lower cut for valence quarks; default : CVQ = 1.0

  **WHAT(2)** = CDQ ; $(x_{qq}^{val})^{min} = \mathrm{CDQ}/\sqrt{s}$,
  lower cut for valence diquarks; default : CDQ = 2.0

  **WHAT(3)** = CSEA; $(x_{q/\bar{q}}^{sea})^{min} = \mathrm{CSEA}/\sqrt{s}$,
  lower cut for sea quarks; default : CSEA = 1.0

  **WHAT(4)** = SSMIMA; $(x_{q/\bar{q}}^{sea})^{target} \cdot (x_{q/\bar{q}}^{sea})^{project.} \cdot s \geq (SSMIMA)^2$,
  lower cut for the mass of sea-sea chains applied in XKSAMP;
  default : SSMIMA = 1.2 $GeV$.

  **WHAT(5)** = VVMTHR; threshold parameter for the mass of v–v chains, comp. Sect. 3.3.1; default: 6 GeV;
  if WHAT(5) < 2 GeV the default value will be used internally.

- Code word = 'FERMI'

  **WHAT(1):** Inclusion of Fermi momenta for nucleons if WHAT(1)= 1.0 (default)

  **WHAT(2):** FERMOD - scale factor for Fermi momentum as calculated from zero temperature Fermi distribution of nucleons;
  default: FERMOD = 0.6.

- Code word = 'START'

  This option starts the generation of events including the output of standard histograms.

  **WHAT(1):** number of events to be sampled; default: 100

  **WHAT(2):** the Glauber initialization is forced to be calculated in SHMAKI, i.e. no data read from file GLAUBTAR.DAT, if WHAT(2) = 1.0

- Code word = 'PARTICLE'

  This card triggers a printout of all the particles defined in the BAMJET-DECAY chain fragmentation, including name conventions, quantum numbers and decay channels.

- Code word = 'STOP'

  This option stops the execution of the program.

## A.2: Sample Input

In the following three typical examples of input data are reproduced. In the first two examples the generation of $p$–$Cu$ and central $O$–$Au$ events, resp., is requested. In both cases 100 events are to be sampled. The last example demonstrates the use of the test program to generate the input data for the Glauber formalism in $p$–$Cu$ collisions.

### Hadron-Nucleus collisions

For illustration several PROJPAR options are shown in this input sample; the last one actually defines the projectile. Further details are explained by the use of COMMENT cards in the input file.

```
TITLE
   DTUNUC TESTRUN  p-Cu   200 GeV/c
PROJPAR                                                          PION+
PROJPAR                                                          PION-
PROJPAR                                                          APROTON
PROJPAR                                                          PROTON
TARPAR          63.        29.
ENERGY         200.
TAUFOR          10.        15.
START          100.
STOP
```

### Central Nucleus-Nucleus collisions

```
TITLE
   DTUNUC TESTRUN  O-AU
PROJPAR         16.         8.
TARPAR         197.        79.
MOMENTUM       200.
TAUFOR          7.5        25.
CENTRAL         1.
START          100.
STOP
```

### Input data for Glauber formalism

```
TITLE
   DTUNUC generation of Glauber input data
TARPAR          63.        29.
GLAUBERI
STOP
```

# Appendix B :
# Event history and the common block /HKKEVT/

## B.1: Structure of the common block

During the generation of individual events several entries are scored in the common block /HKKEVT/ characterizing subsequent stages of the sampling process. Scored entries are, for instance, initial state nucleons, partons and parton chains, decaying resonances as well as final state particles. These entries are characterized by their type, 4-momenta and coordinates; additional pointers define 'parents' and 'daughters' of the actual entry (if any). The structure of this common block closely follows the suggestions of Ref. [19]. Within the code there are extensive comments explaining the variables used in this common block. Below the common block is reproduced together with these comments.
Note that for interactions potentially resulting in high multiplicities of secondaries (i.e. very high energies and/or heavy ion–ion collisions) it may become necessary to increase the dimension NMXHKK, the maximum number of entries for a given event.

```
      PARAMETER (NMXHKK=20000)
      COMMON /HKKEVT/ NHKK,NEVHKK,ISTHKK(NMXHKK),IDHKK(NMXHKK),
     &                JMOHKK(2,NMXHKK),JDAHKK(2,NMXHKK),
     &                PHKK(5,NMXHKK),VHKK(4,NMXHKK),WHKK(4,NMXHKK)
C
C  Based on the proposed standard COMMON block (Sjostrand Memo 17.3,89)
C
C NMXHKK: maximum numbers of entries (partons/particles) that can be
C    stored in the common block.
C
C NHKK: the actual number of entries stored in current event. These are
C    found in the first NHKK positions of the respective arrays below.
C    Index IHKK, 1 <= IHKK <= NHKK, is used below to denote a given
C    entry.
C
C ISTHKK(IHKK): status code for entry IHKK, with following meanings:
C    = 0 : null entry.
C    = 1 : an existing entry, which has not decayed or fragmented.
C        This is the main class of entries which represents the
C        "final state" given by the generator.
C    = 2 : an entry which has decayed or fragmented and therefore
C        is not appearing in the final state, but is retained for
C        event history information.
C    = 3 : a documentation line, defined separately from the event
C        history. (incoming reacting
C        particles, etc.)
C    = 4 - 10 : undefined, but reserved for future standards.
```

```
C     = 11 - 20 : at the disposal of each model builder for constructs
C         specific to his program, but equivalent to a null line in the
C         context of any other program. One example is the cone defining
C         vector of HERWIG, another cluster or event axes of the JETSET
C         analysis routines.
C     = 21 - : at the disposal of users, in particular for event tracking
C         in the detector.
C
C IDHKK(IHKK) : particle identity, according to the Particle Data Group
C    standard.
C
C JMOHKK(1,IHKK) : pointer to the position where the mother is stored.
C    The value is 0 for initial entries.
C
C JMOHKK(2,IHKK) : pointer to position of second mother. Normally only
C    one mother exist, in which case the value 0 is used. In cluster
C    fragmentation models, the two mothers would correspond to the q
C    and qbar which join to form a cluster. In string fragmentation,
C    the two mothers of a particle produced in the fragmentation would
C    be the two endpoints of the string (with the range in between
C    implied).
C
C JDAHKK(1,IHKK) : pointer to the position of the first daughter. If an
C    entry has not decayed, this is 0.
C
C JDAHKK(2,IHKK) : pointer to the position of the last daughter. If an
C    entry has not decayed, this is 0. It is assumed that the daughters
C    of a particle (or cluster or string) are stored sequentially, so
C    that the whole range JDAHKK(1,IHKK) - JDAHKK(2,IHKK) contains
C    daughters. Even in cases where only one daughter is defined (e.g.
C    K0 -> K0S) both values should be defined, to make for a uniform
C    approach in terms of loop constructions.
C
C PHKK(1,IHKK) : momentum in the x direction, in GeV/c.
C PHKK(2,IHKK) : momentum in the y direction, in GeV/c.
C PHKK(3,IHKK) : momentum in the z direction, in GeV/c.
C PHKK(4,IHKK) : energy, in GeV.
C PHKK(5,IHKK) : mass, in GeV/c**2. For spacelike partons, it is allowed
C    to use a negative mass, according to PHKK(5,IHKK) = -sqrt(-m**2).
C
C VHKK(1,IHKK) : production vertex x position, in mm.
C VHKK(2,IHKK) : production vertex y position, in mm.
C VHKK(3,IHKK) : production vertex z position, in mm.
C VHKK(4,IHKK) : production time, in mm/c (= 3.33*10**(-12) s).
```

```
C
C WHKK(4,NMXHKK) gives positions and times in projectile frame,
C    the chains are created on the positions of the projectile nucleons
C    in the projectile frame (target nucleons in target frame);
C    both positions are threfore not completely consistent.
C    The times in the projectile frame ,however, are obtained by
C    a Lorentz transformtion from the lab system.
```

## B.2: Conventions for the scoring of the event history in /HKKEVT/

In the following we briefly characterize the subsequent entries to /HKKEVT/ together with the most important conventions for their classification.

- projectile hadron/nucleons;
  for projectile nuclei Fermi momenta in the projectile rest frame and coordinates within the nucleus are stored in the arrays PHKK and VHKK, resp., by the subroutine KKEVT;
  interacting and non-interacting nucleons have the status ISTHKK=11 and 13, resp.;

- target nucleons;
  Fermi momenta in the target rest frame and coordinates within the nucleus are defined in PHKK and VHKK, resp. (KKEVT);
  interacting and non-interacting nucleons have the status ISTHKK=12 and 14, resp.;

- valence quarks / diquarks from the interacting projectile hadron/nucleon(s) defined in the subroutine XKSAMP (total number IXPV);
  PHKK(3,...)=PHKK(4,...) contains the actual momentum fraction, VHKK the position of the 'mother' hadron;
  defined status ISTHKK=21;

- sea quarks from interacting projectile hadrons defined in XKSAMP (total number IXPS);
  PHKK(3,...)=PHKK(4,...) contains the actual momentum fraction, VHKK the position of the 'mother' hadron;
  defined status ISTHKK=31;

- valence quarks / diquarks from interacting target nucleons defined in XKSAMP (number IXTV);
  PHKK(3,...)=PHKK(4,...) contains the actual momentum fraction, VHKK the position of the 'mother' hadron;
  defined status ISTHKK=22;

- sea quarks from interacting target nucleons defined in XKSAMP (number IXTS);
  PHKK(3,...)=PHKK(4,...) contains the actual momentum fraction, VHKK the position of the 'mother' hadron;
  defined status ISTHKK=32;

- characteristics of the individual parton-parton chains (before hadronization) from subroutines KKEVVV, KKEVSV, KKEVVS and KKEVSS; for each chain there are three entries:
  (1) two entries for the quark systems forming the chain;
  PHKK gives their 4-momenta; the status of the corresponding quark system is increased by 100 as compared to the previous entry from the subroutine XKSAMP (i.e. ISTHKK=121,122,131 or 132 ,resp.);
  (2) one entry for the complete chain;

PHKK gives the total 4-momentum, the 'particle' type for chains is defined to be IDHKK=88888;
the actual status ISTHKK points to the chain generating subroutine:
ISTHKK=3 for chains from KKEVVV (constructed from valence quark systems),
ISTHKK=4 for chains from subroutine KKEVSV (sea-valence chains),
ISTHKK=5 for chains from subroutine KKEVVS (valence-sea chains),
ISTHKK=6 for chains from subroutine KKEVSS (sea-sea chains);

- hadrons from the hadronization of chains, entries from subroutines HADRSS, HADRVS, HADRSV, HADRVV;
  assignment of values to all arrays of /HKKEVT/, status ISTHKK=1;

- hadrons from resonance decay in subroutine DECHKK
  (presently called after completion of the primary interaction of the projectile treated in KKEVT);
  the status of decaying hadrons is changed to ISTHKK=2, added decay products have ISTHKK=1;

- hadrons from intranuclear cascade interactions (monitored by FOZOKL):
  the status of interacting secondary is changed to ISTHKK=2; interacting target nucleons get ISTHKK=12, interacting projectile nucleons with ISTHKK=11; final state hadrons have the status ISTHKK=1.
  Particular cases:

  (i) If a given secondary interaction is found to be forbidden because of the Pauli principle the initial state particles are stored in /HKKEVT/ with their original properties, but the actual position; so they may participate in further intranuclear interactions.

  (ii) One (or two) nucleons from a secondary interaction cannot escape from the nuclear potential, but the particular collision is <u>not</u> forbidden by Pauli's principle (i.e. several nucleons knocked out of the nucleus already):
  Store the nucleon(s) with the actually generated momentum at the collision site, assigning the status ISTHKK=15 (16) for interactions in the target (projectile) nucleus. Those nucleons are available as target (projectile) nucleons in subsequent steps of the intranuclear cascade development.

  (iii) Negative particles with energies too low to escape from the potential are forced to be absorbed within the nucleus (comp. Section 2 and Appendix); absorbed $\pi^-$, $K^-$ and $\bar{p}$ are characterized by the status ISTHKK=19.

The information from this common block allows a rather detailed reconstruction of the actual event history, and is particularly useful for consistency tests and debugging. An example is discussed in Subsection B.3.

## B.3: Sample event history from the common block /HKKEVT/

In this subsection we discuss a typical event history as stored in the common block /HKKEVT/ according to the conventions discussed in the preceding subsection B.2. The corresponding event was sampled for the interaction of a 200 $GeV$ antiproton with a carbon nucleus. The following quantities from the common are listed for each entry: the number $i$ of the entry, its status ISTHKK($i$) and type IDHKK($i$), the pointers JMOHKK(2,$i$) and JDAHKK(2,$i$) to the 'mother' and 'daughter' particles, resp., and the array PHKK(5,$i$), for final state particles containing the 4-momentum and their mass. The first 13 entries are made in the subroutine KKEVT for the incident antiproton and the 12 nucleons from the carbon nucleus. According to our conventions interacting hadrons get the status 11 (projectile) and 12 (target) - there are two nucleons participating in the primary interaction (entries 9 and 11, i.e one neutron and one proton). For these entries the array PHKK(4,$i$) gives the assigned Fermi momenta in the rest systems of projectile and target, resp.:

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 11 | -2212 | 0 | 0 | 0 | 0 | 0.00E-01 | 0.00E-01 | 0.00E-01 | 9.38E-01 | 9 |
| 2 | 14 | 2112 | 0 | 0 | 0 | 0 | 1.68E-01 | -1.78E-01 | 1.76E-01 | 9.87E-01 | 9 |
| 3 | 14 | 2212 | 0 | 0 | 0 | 0 | 3.38E-02 | 6.25E-02 | -1.46E-01 | 9.52E-01 | 9 |
| 4 | 14 | 2112 | 0 | 0 | 0 | 0 | -2.74E-02 | 6.58E-02 | -1.02E-01 | 9.48E-01 | 9 |
| 5 | 14 | 2112 | 0 | 0 | 0 | 0 | 2.63E-01 | 3.10E-02 | 1.06E-01 | 9.82E-01 | 9 |
| 6 | 14 | 2112 | 0 | 0 | 0 | 0 | -1.14E-01 | 1.82E-01 | -1.68E-01 | 9.79E-01 | 9 |
| 7 | 14 | 2212 | 0 | 0 | 0 | 0 | -3.17E-02 | -2.64E-01 | 1.72E-01 | 9.90E-01 | 9 |
| 8 | 14 | 2212 | 0 | 0 | 0 | 0 | -4.79E-02 | -2.53E-02 | 1.51E-01 | 9.52E-01 | 9 |
| 9 | 12 | 2112 | 0 | 0 | 0 | 0 | 7.14E-02 | -1.71E-01 | -2.52E-01 | 9.91E-01 | 9 |
| 10 | 14 | 2112 | 0 | 0 | 56 | 56 | 8.50E-03 | -2.13E-01 | -1.29E-01 | 9.83E-01 | 9 |
| 11 | 12 | 2212 | 0 | 0 | 0 | 0 | 1.74E-01 | 1.47E-01 | -1.11E-01 | 9.72E-01 | 9 |
| 12 | 14 | 2212 | 0 | 0 | 0 | 0 | -2.33E-01 | -8.64E-02 | -8.60E-03 | 9.70E-01 | 9 |
| 13 | 14 | 2212 | 0 | 0 | 0 | 0 | -1.70E-01 | 6.42E-02 | 2.42E-01 | 9.86E-01 | 9 |

The next entries come from the subroutines XKSAMP and FLKSAM (in module DMNUC2) assigning $x$ values and flavor to the quarks participating in the interaction: The antiproton is split into a $\bar{u}$, an antidiquark ($\overline{ud}$) (both with status ISTHKK=21), and two quarks $u$ and $\bar{u}$ from a colorless sea pair (status ISTHKK=31). The interacting target nucleons are split in valence quark-diquark systems: the neutron (entry 9) into $u$-($dd$), the proton (entry 11) into $u$-($ud$). The $x$ values given for each quark system as PHKK(3,$i$)=PHKK(4,$i$) add up to one for each individual hadron.

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 14 | 21 | -2 | 1 | 0 | 0 | 0 | 0.00E-01 | 0.00E-01 | 5.43E-01 | 5.43E-01 | 0 |
| 15 | 21 | -2103 | 1 | 0 | 0 | 0 | 0.00E-01 | 0.00E-01 | 2.87E-01 | 2.87E-01 | 0 |
| 16 | 31 | 2 . | 1 | 0 | 0 | 0 | 0.00E-01 | 0.00E-01 | 7.16E-02 | 7.16E-02 | 0 |
| 17 | 31 | -2 | 1 | 0 | 0 | 0 | 0.00E-01 | 0.00E-01 | 9.81E-02 | 9.81E-02 | 0 |
| 18 | 22 | 2 | 9 | 0 | 0 | 0 | 0.00E-01 | 0.00E-01 | 9.79E-02 | 9.79E-02 | 0 |
| 19 | 22 | 1103 | 9 | 0 | 0 | 0 | 0.00E-01 | 0.00E-01 | 9.02E-01 | 9.02E-01 | 0 |
| 20 | 22 | 2 | 11 | 0 | 0 | 0 | 0.00E-01 | 0.00E-01 | 1.52E-01 | 1.52E-01 | 0 |
| 21 | 22 | 2103 | 11 | 0 | 0 | 0 | 0.00E-01 | 0.00E-01 | 8.48E-01 | 8.48E-01 | 0 |

The following entries come from the routines constructing the colorless parton-parton chains. First the chains are considered (in subroutine KKEVSV) which are composed from projectile sea quarks and target valence quarks. In this example there are two such chains: $u$-$(ud)$ and $\bar{u}$-$u$. The entries are made subsequently for the partons forming the chain and the constructed chain itself, with the array PHKK(5,$i$) containing the corresponding 4-momenta and the mass, resp. The 4-momenta are defined in the cms system of the incident hadron and a single nucleon (without Fermi momentum). By definition these chains get the status ISTHKK=4, the status of quarks/quark systems at chain ends is increased by 100 compared to their previous entries.

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 22 | 131 | 2 | 16 | 1 | 24 | 24 | 2.04E-02 | 1.72E-02 | 7.01E-01 | 7.02E-01 |
| 23 | 122 | 2103 | 21 | 11 | 24 | 24 | 1.06E-01 | 8.99E-02 | -9.48E+00 | 9.48E+00 |
| 24 | 4 | 88888 | 22 | 23 | 34 | 36 | 1.27E-01 | 1.07E-01 | -8.78E+00 | 1.02E+01 |
| 25 | 131 | -2 | 17 | 1 | 27 | 27 | 1.91E-02 | 1.61E-02 | -1.70E+00 | 1.70E+00 |
| 26 | 122 | 2 | 20 | 11 | 27 | 27 | 2.80E-02 | 2.36E-02 | 9.61E-01 | 9.62E-01 |
| 27 | 4 | 88888 | 25 | 26 | 37 | 38 | 4.71E-02 | 3.97E-02 | -7.38E-01 | 2.66E+00 |

In the same manner the next entries describe the chains constructed from valence quark systems of both the projectile and a target nucleon (neutron in this example) in the subroutine KKEVVV. Entries for all chains are marked by the identity IDHKK=88888, valence-valence chains get the status ISTHKK=3.

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 28 | 121 | -2 | 14 | 1 | 30 | 30 | 2.07E-02 | -4.96E-02 | 5.27E+00 | 5.27E+00 |
| 29 | 122 | 2 | 18 | 9 | 30 | 30 | 1.09E-02 | -2.62E-02 | 2.79E+00 | 2.79E+00 |
| 30 | 3 | 88888 | 28 | 29 | 39 | 41 | 2.46E-02 | -5.89E-02 | 4.02E+00 | 6.53E+00 |
| 31 | 121 | -2103 | 15 | 1 | 33 | 33 | 3.59E-02 | -8.63E-02 | -1.16E+01 | 1.16E+01 |
| 32 | 122 | 1103 | 19 | 9 | 33 | 33 | 3.90E-03 | -9.36E-03 | -1.26E+00 | 1.26E+00 |
| 33 | 3 | 88888 | 31 | 32 | 42 | 46 | 4.68E-02 | -1.12E-01 | -8.80E+00 | 1.44E+01 |

The next entries are generated by the routines HADRxx monitoring the chain decay. First the decay of the (two) sea-valence chains is handled via HADRSV: The $u$-$(ud)$ chain (entry 24) fragments into $(K^{*+}, \Delta^0, \bar{K}^0)$, the $\bar{u}$-$u$ chain (entry 27) into $(\pi^-, \pi^+)$. The resonances from the first chain aquire the status ISTHKK=2 after the treatment of their decay; the decay products are found as entries 47-48 and 49-50, resp. After event completion the 4-momenta are given in the laboratory system.

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 34 | 2 | 323 | 24 | 0 | 47 | 48 | -1.76E-01 | 1.37E-01 | 1.22E+01 | 1.23E+01 |
| 35 | 2 | 2114 | 24 | 0 | 49 | 50 | 4.06E-01 | -1.37E-01 | 7.24E-01 | 1.49E+00 |
| 36 | 1 | -311 | 24 | 0 | 0 | 0 | -1.03E-01 | 1.07E-01 | 1.08E+00 | 1.20E+00 |
| 37 | 1 | -211 | 27 | 0 | 0 | 0 | 8.50E-02 | -1.06E-01 | 3.34E-02 | 1.97E-01 |
| 38 | 1 | 211 | 27 | 0 | 0 | 0 | -3.79E-02 | 1.45E-01 | 1.97E+01 | 1.97E+01 |

Following the hadronization of the (two) valence-valence chains the subroutine HADRVV generates the entries:

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 39 | 1 | 321 | 30 | 0 | 0 | 0 | -1.90E-01 | -9.73E-01 | 5.61E+00 | 5.72E+00 |
| 40 | 1 | -211 | 30 | 0 | 0 | 0 | -1.30E-01 | 7.43E-03 | 5.82E+01 | 5.82E+01 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 41 | 1 | -311 | 30 | 0 | 0 | 0 | 3.45E-01 | 9.06E-01 | 4.51E+01 | 4.51E+01 |
| 42 | 1 | -2112 | 33 | 0 | 0 | 0 | -4.84E-01 | -9.30E-02 | 3.75E+01 | 3.75E+01 |
| 43 | 1 | -211 | 33 | 0 | 0 | 0 | -2.92E-02 | -8.57E-02 | 2.52E+00 | 2.53E+00 |
| 44 | 1 | -211 | 33 | 0 | 0 | 0 | 2.54E-02 | -7.30E-02 | -1.72E-01 | 2.34E-01 |
| 45 | 2 | 2214 | 33 | 0 | 51 | 52 | 2.23E-01 | 2.50E-01 | 8.71E-01 | 1.54E+00 |
| 46 | 2 | 223 | 33 | 0 | 53 | 55 | 3.11E-01 | -1.11E-01 | 1.62E+01 | 1.62E+01 |

The next entries are generated by the subroutine DECHKK. It scans the common block /HKKEVT/ for unstable particles, adds the decay products to the common and changes the status of resonances to ISTHKK=2 after their decay. For example, the $\omega$ (entry 46) from the fourth chain (entry 33) decays into $(\pi^+, \pi^-, \pi^0)$ (entries 53-55).

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 47 | 1 | 321 | 34 | 0 | 0 | 0 | 1.07E-01 | 2.71E-01 | 8.31E+00 | 8.33E+00 |
| 48 | 1 | 111 | 34 | 0 | 0 | 0 | -2.83E-01 | -1.34E-01 | 3.92E+00 | 3.94E+00 |
| 49 | 1 | 2112 | 35 | 0 | 0 | 0 | 4.38E-01 | -6.92E-02 | 3.93E-01 | 1.11E+00 |
| 50 | 1 | 111 | 35 | 0 | 0 | 0 | -1.13E-01 | -5.51E-02 | 2.58E-01 | 3.17E-01 |
| 51 | 2 | 2212 | 45 | 0 | 56 | 56 | 4.04E-01 | 1.73E-01 | 7.40E-01 | 1.27E+00 |
| 52 | 1 | 111 | 45 | 0 | 0 | 0 | -1.80E-01 | 7.65E-02 | 1.31E-01 | 2.71E-01 |
| 53 | 1 | 211 | 46 | 0 | 0 | 0 | -4.46E-03 | 1.39E-01 | 4.00E+00 | 4.01E+00 |
| 54 | 1 | -211 | 46 | 0 | 0 | 0 | 2.64E-01 | -2.61E-02 | 9.44E+00 | 9.44E+00 |
| 55 | 1 | 111 | 46 | 0 | 0 | 0 | 5.19E-02 | -2.24E-01 | 2.78E+00 | 2.79E+00 |

The proton from entry 51 undergoes a secondary collision with the neutro from entry 10, the interaction is monitored by the subroutine FOZOKL. The status of the initial state proton is changed to ISTHKK=2, a new entry with the modified 4-momentum is made:

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 56 | 1 | 2212 | 51 | 10 | 0 | 0 | 1.82E-01 | 2.80E-01 | 7.03E-01 | 1.22E+00 |

The target neutron did not gain enough energy to escape from the nucleus Therefore the status of its original entry (number 10) is not changed from 14 to 12; the nucleon is available for further intranuclear cascade interactions.
Eventually the actual final state hadrons are obtained from the common block /HKKEVT/ by picking up all particles with the status ISTHKK=1.

# Appendix C : Treatment of Coulomb energy

To extend the applicability of the model to the energy domain well below 1 GeV an approximate treatment of the Coulomb potential is provided for hadron–nucleus interactions. The Coulomb barrier modifying the nuclear potential is calculated from the following general expression:

$$V_c = \frac{Z_1 Z_2}{4\pi\epsilon_0 \left(A_1^{1/3} + A_2^{1/3}\right)}, \tag{6}$$

resulting for hadron–nucleus collisions ($A_1 = 1, Z_1 = 1$) in

$$V_c \simeq 0.001116 \frac{Z_T}{(1.0 + A_T^{1/3})}\ GeV. \tag{7}$$

At the following stages of event generation effects of the Coulomb potential are taken into account:

**Incident particles:** (Subroutine KKINC)

$Q = +1$: repulsion for $E_{kin} < V_c$, i.e. no hadronic interaction, projectile is directly put into the stack /HKKEVT/ with status $ISTHKK(1) = 1$;

$Q = -1$: the projectile energy is increased by $V_c$ before the treatment of the intranuclear cascade;

**Intranuclear cascade:** (Subroutine FOZOKL)
negative particles (i.e. $\pi^-, K^-$ and $\bar{p}$) with $E < m_0 + V_{nuc} + V_c$ are not allowed to escape from the potential but forced to be absorbed within the nucleus; $\bar{p}$–nucleon interactions are handled by HADRIN, the absorption of negative mesons on two nucleons is treated in the subroutine STOPIK; (absorbed negatives obtain the status $ISTHKK = 19$ for an unambiguous description of the event history);

**Final state particles:** (Subroutine KKINC)

$Q = +1$: positives not allowed to penetrate the Coulomb barrier, i.e. $E < m_0 + V_{nuc} + V_c$, are assigned the residual nucleus with status $ISTHKK = 16$ in the common /HKKEVT/;

$Q = -1$: the energy of negative particles is reduced by $V_c$.

Note that the effects of the Coulomb potential are so far included for hadron–nucleus collisions only.

# Appendix D :
# Two–nucleon absorption of negative mesons

For kinematical reasons the absorption of low–energy mesons within the nucleus requires the interaction with two–nucleon systems. The following reaction channels are considered in the subroutine STOPIK:

**$\pi^-$ absorption:**

$$\begin{aligned} \pi^- + p + p &\rightarrow n + p \\ \pi^- + p + n &\rightarrow n + n \end{aligned}$$

**$K^-$ absorption:**

$$\begin{aligned} K^- + p + p &\rightarrow \Sigma^+ + n \\ &\rightarrow \Lambda + p \\ &\rightarrow \Sigma^0 + p \\ K^- + p + n &\rightarrow \Sigma^- + p \\ &\rightarrow \Lambda + n \\ &\rightarrow \Sigma^0 + n \\ K^- + n + n &\rightarrow \Sigma^- + n \end{aligned}$$

Momenta of the final state baryons are sampled from phase space distributions in the rest system of the three initial state particles.