

Internal Report

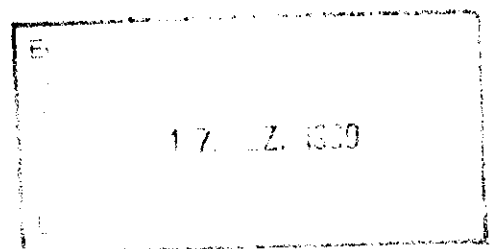
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User's Guide for the FLUNEV Code:

An Extension of the FLUKA High Energy Particle  
Shower Code to Calculate Production and Transport  
of Secondary Neutrons Below 50 MeV and Gammas  
of Nuclear Origin

J.M. Zazula



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Shower Code to Calculate Production and Transport  
of Secondary Neutrons Below 50 MeV and Gammas  
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VERSION: December 2, 1990

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**Abstract**

The following manual gives guidance to the FLUNEV code, a DESY-D3 extension of the FLUKA90 hadronic shower Monte Carlo code (developed at CERN) to calculate production and transport of secondary neutrons below 50 MeV and gammas of nuclear origin, which is useful for radiation protection and detection and for design of accelerator shielding. The document contains description of added and modified modules, of the extended user input parameters, of additional input data files, of enhanced scoring and output options and of the computer hardware and software requirements. Features of the original FLUKA code are not considered here. The job control and user input cards and the tabulated results of a sample problem are included in the Appendixes.

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## Code Abstract

### Name and title:

FLUNEV Code: An Extension of the FLUKA High Energy Particle Shower Code to Calculate Production and Transport of Secondary Neutrons Below 50 MeV and Gammas of Nuclear Origin

### Date of abstract:

December 2, 1990

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### Coding language and computer:

FVS FORTRAN; IBM . Models 3084/3090, System MVS/NEWLIB

### Nature of problem solved:

FLUNEV is a Monte Carlo particle transport code coupling together calculations of the high energy particle cascades and of the low energy neutron and photon production and transport. It can be applied for solving problems of radiation protection, radiation detection and shielding design at high energy accelerators. FLUNEV has enhanced options for scoring the particle fluences, absorbed doses and dose equivalents from different radiation components and it has been interfaced with the GEP graphic package, for bookkeeping neutron and gamma fluence and dose spectra.

### Method of solution:

FLUNEV is linking into one program the Monte Carlo hadronic shower code FLUKA90 (above 50 MeV), including also the EGS4 code for electromagnetic cascades, the Monte Carlo nuclear evaporation module EVAP-5 and gamma deexcitation module NDEM (taken both from the HERMES code system), and the low energy (below 50 MeV) neutron transport module based on the FLUKA geometry packages (cylindrical, cartesian or combinatorial), the collision and cross section package extracted from the Monte Carlo neutron transport code MORSE (ORNL), and the multigroup neutron cross section library HILO86 supplied by the MACKLIB-IV and other kerma factor data. For further details the user is referred to the FLUNEV description and the documentation of component codes.

### Restrictions and limitations:

Accuracy of FLUNEV is affected by validity of models included in the coupled FLUKA, EGS, EVAP, NDEM and MORSE codes. Electro- and photoproduction of hadrons, nuclear multifragmentation

and preequilibrium secondary emission are not sampled in the current version. In the low energy neutron transport module 45 neutron and 22 gamma group cross sections (averaged over possible nuclear reactions), with  $P_5$  Legendre expansion, are available only for 18 elements: H, 10-B, 11-B, C, N, O, Na, Mg, Al, Si, S, K, Ca, Cr, Fe, Ni, W and Pb, or their compounds. Time dependence is not considered. Biasing techniques used in the MORSE code are not implemented.

## Computer hardware and software requirements:

FLUNEV is the FORTRAN77 code written in double precision: it has been compiled by FVS compiler and run on IBM-3084 and IBM-3090 machines under MVS system. It requires about 8000 Kb memory. CERNLIBRARY subroutines are called and GEP graphical package is interfaced (it can be, however, abandoned). 3 external binary data files are used (containing the nuclear model parameters and the processed multigroup cross sections). Running times are strongly dependent on the problem to be solved and on the desired accuracy: for the DESY computers they varied from minutes to hours: factor of 2 or more per beam particle is to be expected when comparing with the calculation times of original FLUKA code with 50 MeV lower energy cutoffs, for the same problem.

## Contents of the code package:

Source versions of the original, added and modified modules; the job control cards and user input cards for a sample problem; the EBCDIC formatted input data files and the job cards and codes creating their binary versions.

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# 1 General remarks

Hadronic cascade codes suffer from a low energy cutoff (50 - 20 MeV) too high for shielding design and other radiation protection problems at present-day high energy accelerators, since the emission and propagation of low energy neutrons dominates many quantities of practical interest (particle fluences, dose equivalents, radiation damage *etc.* ).

We describe here our special version of the Monte Carlo (MC) shower code FLUKA [1]<sup>1</sup> (originated in Leipzig University and extensively developed at CERN), the FLUNEV code, linking together:

1. The original high-energy event generator (modified by reducing both the energy of intranuclear cascade and the excitation energy, according to experimental results) and the original high energy particle transport, geometry and scoring modules;
2. The nuclear evaporation module (accounting also for high energy fission) EVAP-5 and the gamma deexcitation module NDEM for emission of secondary neutrons below the original threshold energy and of the photons of nuclear origin: both taken from the HERMES code system [2] of KFA Jülich and supplied by an external data files containing the nuclear parameters.
3. The low energy neutron transport module, based on the FLUKA geometry modules, the neutron collision package taken from the MORSE code [3] (originated in ORNL), and the low energy part (from 50 MeV down to 0.4 eV) of the HILO86 multigroup cross section library [4], supplied by the kerma factor data [5,7] and by the data converting particle fluences to ambient dose equivalents [8].

The simplified flow diagram for sampling of the low energy neutrons and gammas within the FLUNEV code is shown in Fig. 1, and the indicated program modules are described in Section 2 of this document.

Our code is an advanced attempt to follow neutrons in energy range of 12 orders of magnitude (1 TeV down to 1 eV) within one MC program. It has been verified by comparison with experimental results from high energy proton beams incident on thin and thick targets, and applied for calculating the following magnitudes of practical interest:

1. Neutron and gamma fluence spectra, dose equivalents and attenuation lengths outside lateral shields of ordinary concrete, heavy concrete and iron, at high energy proton accelerators;
2. Neutron and gamma fields around proton beam absorbers;
3. Neutron contribution to the radiation dose and damage in an accelerator tunnel.

Examples of the FLUNEV code results for the problems mentioned above can be found in our research reports [15-20]. Good agreement with measured data and earlier calculations was achieved in most cases.

There are many physical assumptions and several limitations when using FLUNEV code. Some physical processes like photo- and electroproduction of hadrons, multifragmentation of

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<sup>1</sup>The basic version of FLUKA86 has been exchanged to the tentative release of 1990 (January), kindly provided by A.Fasso and A.Ferrari from CERN/TIS-RP

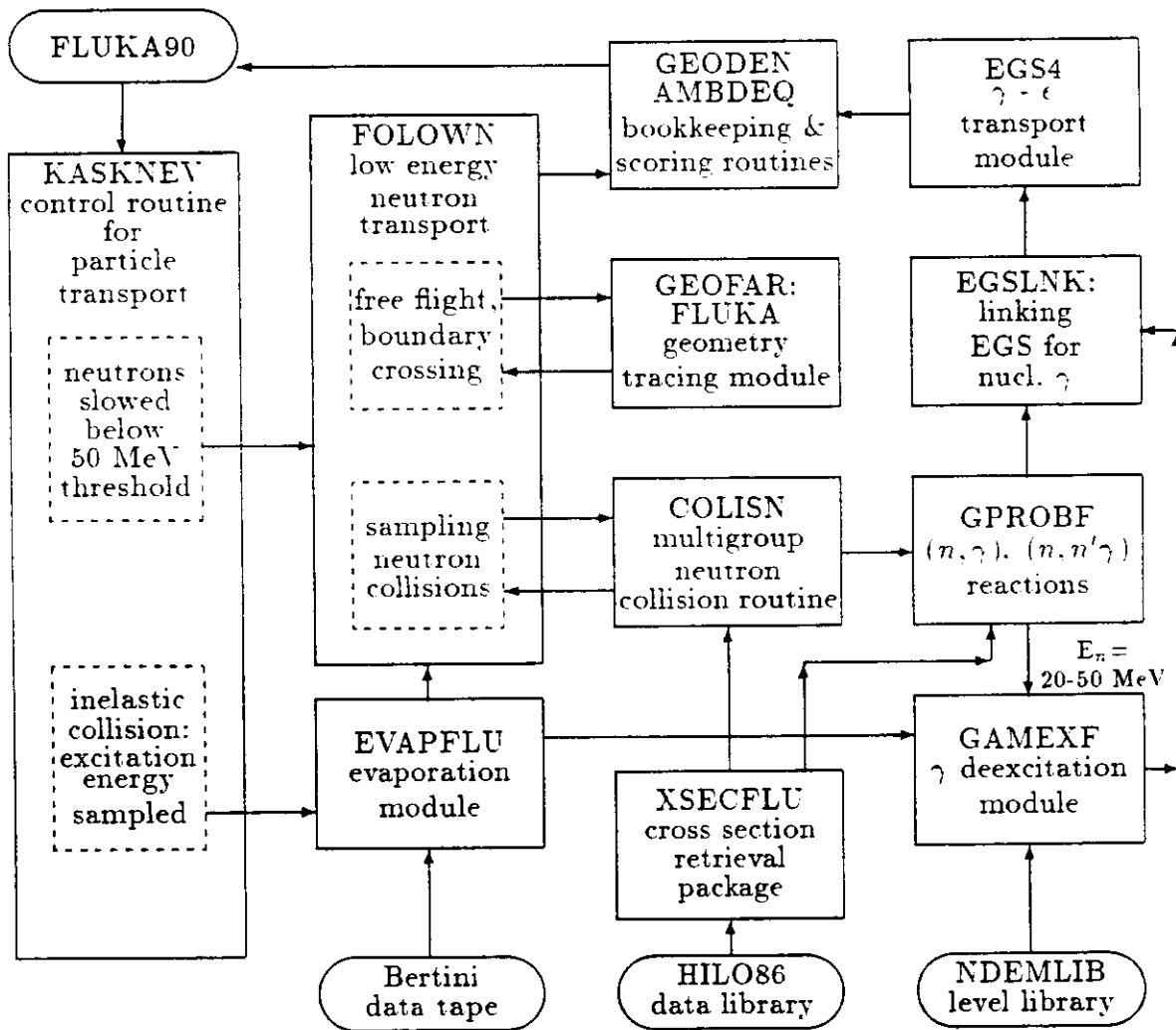


Figure 1: Simplified flow diagram for sampling of the low energy neutrons and photons of nuclear origin in the FLUNEV code.

hot nuclei [13] or emission of secondaries from pre-equilibrium nuclear states have still not been accurately accounted for in the inelastic event generator. The implemented statistical model of nuclear evaporation assumes re-equilibrium of energy between nucleons after successive emissions of neutrons, protons or heavy fragments (which is not a valid physical picture for light elements). The input parameters used for the EVAP module in FLUNEV code include the excitation energy which is obtained from the FLUKA inelastic collision model (EVENTQ), and the mass number of the residual nucleus left after the high energy particle emission and after the intranuclear cascade: the mass number is calculated from baryon number conservation. Although the energy is conserved event by event in this model, the momentum conservation is fulfilled only on the average. Sampling of the intranuclear cascade and excitation energies in FLUNEV version of EVENTQ generator has been readjusted (see Section 2.2 and Ref. [17]) following recent phenomenological suggestions [11-12], to get better agreement with secondary neutron yields and residual nuclei mass distributions measured in



thin targets.

Sampling low energy neutron random walk in large systems is a very time consuming process. Therefore the new user input option implemented in FLUNEV, saving effectively computer time, is specifying the region-dependent lower energy cutoffs for neutron transport simulation. When emitted from a collision with an energy below the threshold assigned to the current geometry region, neutrons are assumed to be absorbed and deposit all their and secondary energy within the next free flight path, if they do not escape or reach another region by chance. Neutrons in the thermal group are assumed to be absorbed within one (infinite medium) diffusion length from the position where they have been slowed down (if they do not escape by chance). This new neutron threshold option of FLUNEV, together with the nuclear gamma production, is introduced as an additional parameter on the ASSIGNMA user-input card describing properties of a range of geometry regions: there are not new input cards recognized in FLUNEV when comparing with FLUKA (see Section 3 for minor changes and extensions in parameters of other options).

Using this option only the most penetrating component can be propagated through a bulk shield, and the component which is likely to be absorbed before contributing to the dose can be neglected. However, the energy limits should be set up below the energy range for which the neutron attenuation lengths are substantially longer than for lower energies, thus they significantly depend on material and on the solved problem. Regions where a response contributed by the whole neutron and photon energy range is of interest should have dimensions large enough (at least comparable with the slowing down length of the fast neutron component) to assure the equilibrium character of the relevant neutron spectra. The same remark concerns also the nuclear gamma production which is also optionally switched on or off in the user-specified regions.

The 45 neutron group and 22 gamma group cross sections with  $P_5$  Legendre expansion are available with FLUNEV only for 18 elements: H,  $^{10}\text{B}$ ,  $^{11}\text{B}$ , C, N, O, Na, Mg, Al, Si, S, K, Ca, Cr, Fe, Ni, W and Pb. These cross sections and the respective kerma factors appear in used multigroup data collections as averaged over energy intervals and over most of possible nuclear reactions, and therefore distinguishing between different secondary particles produced in low energy neutron reactions (important for detector studies) is unfortunately not possible in FLUNEV. The energy group structure can be found in the original documentation [4]. In future versions the lower energy cutoff of FLUKA is to be extended down to 20 MeV (which is the upper energy limit of the ENDF/B Evaluated Neutron Data Files) and then many other available cross section libraries could be used in FLUNEV.

Geometry modules currently available with FLUNEV are the cylindrical and the rectangular. The electromagnetic cascades are accounted for by the FLUKA parametrization or by coupling with EGS code [6]. The time dependences are not considered in our code. Since the absorption or multiplication of a low energy neutron in a single reaction is represented by modifying its statistical weight, the energy conservation is fulfilled only for a large number of neutron collisions. Except for the nonanalog absorption of slow neutrons (see Section 2.5) all the advanced biasing techniques available in the MORSE code (the Russian roulette, splitting, path length stretching and importance sampling) have temporarily been abandoned in FLUNEV, since some first trials showed that they did not give apparent benefits for statistical errors and computing times. Their physical and statistical background require further investigations.

The features of the original FLUKA code are not considered in this document; the reader is referred to the original materials and it is assumed here that he is familiar with the FLUKA User's Guide [1]. The program modules added or modified in FLUNEV are described in Section 2 of this manual: particularly, changes in inelastic collision module in Subsection 2.2, features of the evaporation model in Subsection 2.4, the low energy neutron and gamma transport and cross sections are the subject of Subsection 2.5, 2.6 and 2.7, and the enhanced options for scoring the radiation protection magnitudes are explained in Subsection 2.7. The changes in user input data to FLUNEV, relative to FLUKA are listed in Section 3, and the additional input data files required by FLUNEV are given in Section 4. Extensions of output, printed or stored on data sets, and an interface with GEP [10] graphic package are the subject of Section 5, and the operating system, computer time and memory are considered in Section 6. The last section contains description of a sample problem. The job control cards and user input cards for a sample run, its tabulated results and contents of the source directory are included in the Appendixes.

## 2 Additional and changed program modules in FLUNEV

### 2.1 Changes in main program

*Modified subroutines:* FLUKA

*New subroutines included:* none

*Other new subroutines called:* <sup>2</sup> BERTTP[EVAPFLU], XSECFL[XSECFLU], GEPIC[GEP], GEPW[GEP], DST0[GEP], DST1[GEP], BINS2[GEP]

*New COMMON blocks:* HETTP, SAMPLN, CONTLN, RUNTIT, EBISCO

Some minor changes have been introduced to the main program of FLUKA, included in the FLUNEVG module. No new types of user input cards are added; two are extended and two other are changed (see Section 3). Three new subroutines are added at the end of input section: BERTTP and NDEMFL reading in the nuclear parameters and XSECFL reading in the multigroup data (see Sections 4.1 and 4.2): both providing extra printouts. The GEP graphical package initialization (see Section 6) is another additional task performed in the main program. Double precision is used by IMPLICIT everywhere; RNDM2 is the recommended uniform random number generator from (0,1) interval, linked from CERNLIBRARY and called consistently everywhere. An additional protection against a time limit overflow is assured by the subroutine JUHR from DESY FVS library, asynchronously checking remaining cpu time and calling the rescue subroutine USERTM 10 sec before end of run for saving the results. 20 new COMMON blocks and 2 new BLOCK DATA are included in FLUNEV version of FLUKA, but only 4 are useful in FLUNEVG. The most important changes and extensions of the FLUKA code are mentioned in the following subsections and they are additionally commented in the source listing of FLUNEV.

### 2.2 Changes in EVENTQ event generator

*Modified subroutines:* EVENTQ, NUCRIN, BEKEKA

*New subroutines included:* CORRIN

*Other new subroutines called:* none

*New COMMON blocks:* CORINC

In the current version of FLUNEV code we decided to abandon the original FLUKA parametrization of the intranuclear cascade energy and to follow exactly Alsmillers' modifications [12]. Their main assumption stimulated by empirical observations was that the total energy carried by the intranuclear cascade neutrons and protons can be correlated with a number of collisions of the projectile particle with nucleons of the target nucleus. This parameter is sampled event-by-event in function NUDIST of FLUKA, currently called by the new subroutine CORRIN after entering EVENTQ generator. In addition to the correlation, some phenomenological factors (provided in the DATA statement of CORRIN, according to the values tabulated in Appendix of Alsmillers' report), dependent on the target mass and on the projectile particle, are used for further reduction of the intranuclear cascade energy, to match the measured multiplicities of "gray" particles. After reducing the total energy, the emitted cascade neutrons and protons are sampled in the subroutines NUCEVT (the parton model; above 5 GeV/c) or NUCRIN (the intermediate energy model) of EVENTQ module.

<sup>2</sup>the modules including them are given in brackets

Another modification relative to FLUKA concerns the excitation energy after inelastic collision. TV. In subroutine CORRIN we followed the assumption made by Barashenkov *et al.* [11] that the excitation energy is proportional to the number of "wounded" (hit by projectile) nucleons. We correlated it with the randomly sampled number  $n$  of projectile collisions inside a nucleus using the exponential distribution proposed by Campi [13, see equation (2.3)]:

$$f(E_{ex}) = \frac{1}{(n-1)!} \frac{E_{ex}^{n-1}}{E_0^n} \exp\left(-\frac{E_{ex}}{E_0}\right) \quad (1)$$

accounting for excitation energy fluctuations. This is accomplished by the FUNCTION EXDIST called from CORRIN. A certain semi-empirical amount  $E_0$  of excitation energy per wounded nucleon was assumed by us to be a slowly increasing function of the atomic mass  $A$  of the target:

$$E_0 \simeq c A^{1/2} \quad (2)$$

as it was originally done in the FLUKA parametrization below 100 MeV: no dependence of the excitation energy on the projectile energy below 100 MeV is assumed. The coefficient  $c$  was readjusted in function BEKEKA (included in the INTRAM module of FLUKA) to 6 MeV, providing a better consistency of evaporated neutron yields and residual nuclei masses with other data (see Ref. [17]). As a consequence, in FLUNEV both the energies, carried by the intranuclear cascade and spent for the excitation, are cross-correlated. The kinematical limits for the excitation energy are further tested (an additional condition, important for low incident energies, is that  $E_{ex}$  cannot exceed the projectile particle energy) in the subroutines BEKEKA, NUCEVT or NUCRIN, and then it is transferred back in TV variable of COMMON /FINUC/ to the KASKNEV module.

## 2.3 KASKNEV - particle transport control subroutine

*Modified subroutines:* KASKAD

*New subroutines included:* FOLOWN

*Other new subroutines called:* ERUP[EVAPFLU], AMBDEQ[EPILOGN], HIST[GEP], CORR[GEP]

*New COMMON blocks:* HETC5, HETC7, HETTP, EVA1, LABCOS, CORINC, EVASCO, SAMPLN, CONTLN

KASKNEV module contains a special FLUNEV version of the FLUKA control subroutine for particle transport, KASKAD. The most important changes are made in the following two sections of the original subroutine:

1. After an inelastic collision (labels 400-499) between particle and nucleus (except than hydrogen), the total energy, momentum (assuming four-momentum conservation) and atomic and mass numbers (assuming charge and baryon number conservation) of the residual nucleus left after the high energy particle emission and after the intranuclear cascade are calculated additionally. The latter two values, APR and ZPR, together with the excitation energy  $E_{ex}$  (transferred as TV from the inelastic collision module, EVENTQ; see the last subsection for a modification) are further transferred (by COMMON /HETC5/) to subroutine ERUP, activating the evaporation module (see next subsection). Note that the energy units between

FLUKA modules and EVAP should be converted from GeV to MeV, and back when returning. The subroutine FOLOWN performing the low energy neutron transport is called for each evaporated neutron, with its position coordinates, direction components, energy, weight and current region given as input parameters. The energies of evaporated protons and heavy fragments as well as the excitation and recoil energies of the residual nucleus after evaporation contribute the energy deposited at the collision site (scored additionally by subroutines GEODEN and AMBDEQ). The evaporated neutrons and protons are included also (by subroutine FLUX) in the secondary production counters. The histograms of excitation energies, residual nuclei masses and evaporated neutron energies are booked by GEP package subroutines HIST and CORR (see Section 5). The residual excitation energy after evaporation of the massive particles as well as the atomic and mass numbers of the residual nucleus are the input parameters of the subsequently called gamma deexcitation subroutine, GAMEXF (NDEMFLU module).

2. After a neutron is slowed down below the FLUKA energy threshold for transport process (labels 600-699), the FOLOWN low energy neutron transport subroutine is called with the current neutron position, direction, energy, weight and region given as input parameters. As in the original KASKAD, 1/3 of the energy of any other non-decaying particle falling down below the threshold is deposited locally, and 2/3 of its energy is transformed into one isotropically emitted neutron, and further transported by subroutine FOLOWN.

If no low energy neutron transport has been activated (by specifying the relevant threshold below 50 MeV, see Section 3.1) the standard FLUKA treatment of the evaporated neutron energy and of the threshold neutron energy (1/3 deposited locally and 2/3 within one inelastic interaction length) is used instead of the FOLOWN subroutine.

## 2.4 EVAPFLU - evaporation module

*Modified subroutines:* none

*New subroutines included:* BERTTP, ERUP, DRES, DRESF, GETRIG, QNRG, DOST, ENERGY, ENRG, EXPRNF, BLOCK DATA

*Other new subroutines called:* none

*New COMMON blocks:* HETC5, HETC6, HETC7, HETTP, EVA0, EVA1, LABCOS, INPFLG, FORCN, AZ, FISHUN, SEED, EVASCO, blank

The evaporation code EVAP-5 is based on the Weisskopf theory extended by many others, finally by the KFA Juelich group [2] as a part of their HETC version, from where it was adopted by us. Competition with high energy fission is also accounted for by using RAL model of Achinson (see [2] for references). The updated nuclear model parameters (see Section 4.1 and referred documentation) are read from a special data set (called Bertini tape) by subroutine BERTTP, called from the main program (FLUNEVG). An excitation energy EX, a mass number APR and an atomic number ZPR of the pre-evaporation nucleus are provided by COMMON /HETC5/ to the control subroutine of evaporation module, ERUP, from the calling subroutine, KASKAD. The nuclear mass in MeV is computed internally in subroutine DRES accounting for the binding energy by function ENERGY. The sampled

energies and directions of succeeding evaporated neutrons, protons and heavy fragments (*a.d.t.*<sup>3</sup>*H* $\epsilon$ ) are given on output of DRES in COMMON /EVA1/. A special version of DRES, the DRESF subroutine, is called if the high energy fission is to be considered. When leaving ERUP, the same variables APR and ZPR contain the mass and atomic number of the residual post-evaporation nucleus; its excitation energy UU and recoil energy EREC are also determined. The mean values of excitation energies before and after evaporation and of the yields and energies of evaporated particles, averaged over all inelastic interactions in the system, are printed at the end of FLUNEV run by extended subroutine EPILOG. EVAPFLU module contains its own BLOCK DATA.

## 2.5 FOLOWN - low energy neutron transport subroutine

*Modified subroutines:* none

*New subroutines included:* FOLOWN

*Other new subroutines called:* RETSIG[XSECFLU], COLISN[XSECFLU],  
AMBDEQ[EPILOGN], HIST[GEP]

*New COMMON blocks:* MORSEC, MACSIG, SAMPLN, CONTLN

The special subroutine FOLOWN has been written by us to follow low energy neutrons within the FLUNEV code. It is called (see Fig. 1) from the extended particle transport control subroutine KASKAD (KASKNEV module) each time the neutron falls below the 50 MeV energy limit, or when it is produced by an evaporation process, with the current neutron position, direction, energy and weight set as input arguments. Neutrons are tracked in FOLOWN between the collisions and region boundaries using the original FLUKA geometry package (GEOFAR, MOVE and related routines). Their energy range from 50 MeV to 0.4 eV (assumed for thermal neutrons) is divided into intervals (the energy groups). The corresponding total interaction lengths (for the thermal group replaced by the diffusion length) are retrieved from core by the subroutine RETSIG (XSECFLU module). Changes of the energies and directions in subsequent collisions are controlled in FOLOWN by calling the subroutine COLISN (XSECFLU module) adapted from the MORSE multigroup code. Scoring of neutron fluences and doses is accomplished by subroutine GEODEN of FLUKA and by the enhanced scoring subroutine AMBDEQ.

The following events are recognized by subroutine FOLOWN during neutron random walk:

1. Neutron appears below 50 MeV when entering FOLOWN. Its energy group is determined and the corresponding macroscopic total cross section is retrieved by RETSIG.
2. Neutron free flight path is sampled from exponential distribution. It is moved by MOVE to the next interaction point (item 4) or the nearest region boundary crossing point (item 3), determined by GEOFAR. The tracklength estimator of neutron fluence is contributed (if required by user) by GEODEN.
3. Neutron crosses a region boundary. The surface crossing estimator of neutron fluence is contributed (if required by user) by GEODEN and contribution to dose equivalent (estimated by conversion factors) is calculated by AMBDEQ. If the entered region (determined by GEOFAR) is an internal void neutron traverses it

towards the next region boundary (item 2), and if the entered region is an external void neutron escapes from the system (its history is terminated). Control returns to item 2.

4. Neutron reaches a collision site. The collision density estimator of neutron fluence is contributed (if required by user) by GEODEN. If the current energy is below the region-dependent threshold (specified by user on the ASSIGNMA input cards and stored in ETLN matrix of COMMON (SAMPLN)) the neutron energy is assumed to be deposited locally (by GEODEN) and its further history is terminated. Otherwise, the post-collision direction and energy group are randomly sampled by COLISN using the probability distributions taken from the cross section arrays of core. Note that an element on which collision occurs is sampled randomly from the isotopic composition of a compound material. The particle weight is multiplied by the nonabsorption probability or neutron multiplicity at subsequent collisions instead of killing it randomly (nonanalog absorption). A deposited energy according to the kerma factor is scored by GEODEN and AMBDEQ. Eventually, secondary gamma emission is sampled by subroutine GPROBF. Then control returns to item 1.

## 2.6 NDEMFL, GPROBF - implementation of nuclear gamma emission

*Modified subroutines:* EGSLNK

*New subroutines included:* GPROBFL, NDEMFL, GAMEXF, GAMMA, LEV, CONPRB, REJGAM, GETA, MSPIN, TRNS, PGS, FINT, FMAX, SKEME

*Other new subroutines called:* none

*New COMMON blocks:* PHOTEM, NDAS, SUMRY, IOPUT, BIG1, BIG2, BIG3, BIG4, GROSS1, GROSS2, GA, DATA1, REPEAT, NEW, DATAPS, PSS

Another extension of the FLUNEV version of FLUKA code is incorporation of the secondary photons emitted from the nuclei excited in inelastic collisions and from the low energy neutron reactions like inelastic scattering or radiative capture. Emission and transport of these nuclear gammas can optionally be switched on by a user of our code by assigning the negative sign to the neutron energy threshold (WHAT(6)) on the ASSIGNMA input card. Specification of the regions for which gamma production is of interest and the lower energy cutoffs for electron and photon transport (EGSCUT input card of FLUKA) is a problem-dependent task to be considered by the user.

Gamma emissions from the neutron reactions are accounted for in the neutron to gamma transfer matrixes included in the HILO library. The energy range of photon cross sections in HILO covers 22 energy groups from 20 MeV down to 10 keV, however the gamma production data are unfortunately limited only to neutrons below 20 MeV (for overcoming this problem see the note in further part of this section). Emitted gammas are sampled by the subroutine GPROBF adopted from the MORSE code and called from the neutron transport subroutine FOLOWN after each neutron collision. The number of generated photons corresponds to the integer part of the multiplicity given by the neutron to gamma transfer cross section in the respective neutron group (retrieved from the library data storage); the Russian roulette is played for emission of the last photon respectively to the fractional part of the yield data. The

energy group of emitted photon is chosen randomly from the transfer probability matrix and its direction is sampled from the isotropic distribution since anisotropic gamma production data have not been available. Each gamma has assigned a weight that is equivalent to the weight of the incident neutron before the collision: the importance sampling scheme found in the original MORSE subroutine is not used in our version. Weights and energies of created gammas are included in the energy balance and other counters of our code; bookkeeping the histogram of emitted gamma spectrum is also optionally available (GEP destination 6).

The same input and output code options concern the photons produced from nuclear deexcitations. These processes are accounted for by interfacing to FLUKA environment the NDEM module [2] of the HERMES code system. The NDEMFL subroutine called from main program initializes this module before beginning of the cascade simulation and reads in an additional data set (tape 30) containing the nuclear level, shell and pairing energy data. However, only the lowest option from the few available physical models of NDEM is fixed to be used in our version, assuming no discrete line gamma spectrum but rather a continuum of nuclear states above the pairing gap of the excited nucleus. In this manner the use of this additional module is made as simple and fast as possible, and an amount of the required data is substantially reduced. Moreover, the input parameters which are the excitation energy and the atomic and mass numbers of the excited nucleus are provided only to some extents of accuracy which cause that the results of possible finer deexcitation models would be not more reliable than the simplest level. The emission of deexcitation gammas is controlled by the new subroutine GAMEXF called from KASKAD after the evaporation phase of an inelastic event, leaving a still excited residual nucleus, is completed; simultaneous competition of the massive particle and photon deexcitation modes is not considered as well as the nuclei lighter than helium. The number and energies of photons are sampled by the subroutine GAMMA of NDEM and transferred back by common /PHOTEM/, and the directions are selected isotropically. Note that the energy units of NDEM module are MeV.

In current version, the same deexcitation module is used also for the completion of lacking gamma production from the neutron collisions in energy range between 50 and 20 MeV. The essential point of our approach is the crude assumption that each struck nucleus becomes excited to the energy which is roughly approximated by subtracting the energies of emitted secondary neutrons and charged reaction products including recoil (given by neutron kerma factors) from the projectile neutron energy. The reaction Q-values, not available from the used data library, are neglected here. Moreover, since the energy is conserved only as averaged over many neutron collisions, it can unfortunately occur that for some single events the energy balance is negative, and these cases are rejected in the current version. The resulting energy is deexcited by calling GAMEXF subroutine after neutron collision, instead of GPROBF.

The produced photons can be further transported by the EGS module linked to FLUKA. This approach enables possibly lower energy cutoffs than the multigroup method and it provides more accurate description of the energy deposition processes: moreover, the photon kerma factor data are thus not required. Both the gamma emission subroutines, GPROBF and GAMEXF tag the photon of nuclear origin (by assigning the particle type number 26 to it) and call the subroutine EGSLINK immediately after it is produced. Tagging of these photons is useful to distinguish their contributions to the absorbed dose and dose equivalent from the contribution of the electromagnetic cascade initiated by high energy processes. Scoring of the photon fluences or currents, spectra and doses is accomplished by implementing calls of the



AMBDEQ scoring subroutine to the AUSGAB subroutine of EGS. The photon flux to dose conversion factors in energy range 10 keV to 1 GeV are taken from the ICRP publications [9]; note that they concern a phantom irradiated by a parallel field. The region-dependent lower energy thresholds for the photon transport can be set up by using the EGSCUT input option of FLUKA.

## 2.7 XSECFLU - multigroup neutron and gamma cross section and collision module

*Modified subroutines:* none

*New subroutines included:* XSECFL, XSPRIN, XSTAPE, GTMED, RETSIG, COLISN, GTISO, AZIRN, FLTRNF, BLOCK DATA

*Other new subroutines called:* none

*New COMMON blocks:* MACSIG, LOCSIG, LOCKSEC, DEFMAT, CONTLN, SEED

The multigroup neutron cross sections and kerma factors are linked from an external input file (see Section 4.2 for contents and preparation) by the subroutine XSECFL adapted from MORSEC package [3], called by the main program (FLUNEVG). Particularly, the microscopic data are read by the subroutine XSTAPE called by XSECFL, and then they are mixed in XSECFL to the macroscopic cross sections and kermas, by using the compositions and densities specified by the standard user input options (MATERIAL and COMPOUND) of FLUKA (FLUNEV). Note that all the composite materials should be defined as the COMPOUNDS (*e.g.*, the standard FLUKA materials AIR or CONCRETE are not accepted), and all single elements should have assigned material indices lower than the first composite material. A warning is printed if some of the required isotopes are not available in HILO86 data. Total interaction lengths of neutrons below 50 MeV and photons below 20 MeV and released energies of charged secondaries versus neutron group are printed optionally, and an extra printout may be obtained from subroutine XSPRIN by changing to 1 the IPRIN control variable of COMMON /LOCSIG/ in BLOCK DATA.

The subroutines RETSIG and COLISN, called from the low energy neutron transport module (FOLOWN) with incoming neutron energy group and direction as the parameters, retrieves correspondingly the total cross section and kerma factor, and samples and returns the post collision parameters (weight, energy and direction). The subroutine GTMED (called by COLISN) selects randomly an isotope for which neutron collision occurs, for a compound material. The GPROBF subroutine samples energies and directions of gamma rays emitted from neutron collisions and calls EGSLINK for their further transport. COLISN and GPROBF subroutines (they were simplified for FLUNEV usage) and the relevant core arrays contained in COMMON blocks /MORSEC/ (cross sections) and /LOCSIG/, /LOCKSEC/ (addresses) are described in MORSE code documentation [3]. Note that the XSECFLU, KASKNEV, and EPILOGN modules involve several initializations performed in their common new BLOCK DATA.

## 2.8 AMBDEQ,EPILOGN - enhanced scoring and output subroutines

*Modified subroutines:* EPILOG

*New subroutines included:* AMBDEQ, EPITAF, TABDET

*Other new subroutines called:* HISTGEP

*New COMMON blocks:* SAMPLN, CONTLN, FDSCOR, EVASCO, RUNTIT, EBISCO

Scoring of the dose contributions from different radiation components is the essential and extended task performed by our code when applied to the radiation protection area. In general, the methods of estimation depend on the quantity of interest, on the physical processes, on types of the particles and on the energy range, as it is described below.

### *Absorbed dose*

Scoring of the absorbed dose directly from particles above 50 MeV has not been changed against FLUKA defaults. Their deposited energy consists of two components:

1. Ionization energy losses of charged particles: the distance between subsequent collisions is divided into steps, and at each step the energy of a particle is reduced according to the stopping power formula; the energy lost is deposited in the midpoint of the step. Scored from KASKNEV, after a charged particle flight (the tracklength flux estimating method) by the old subroutine GEODEN, and by the new subroutine AMBDEQ.
2. The energy deposited from the electromagnetic cascade is sampled from semi-empirical formulas describing the radial and longitudinal distributions (or the EGS system is called). Scored from KASKNEV, by GEODEN.

One part of the absorbed dose from high energy neutrons is included in the first component as the energy of their charged secondaries, another part is due to deexcitation of residual nuclei after the neutron inelastic interactions. The excitation energy together with the energy of particles falling below the threshold is the third component of the absorbed dose calculated by the original FLUKA, and treatment of this contribution has significantly been improved in FLUNEV.

In the KASKNEV module the energy of evaporated protons, heavy fragments ( $\alpha$ ,  $d$ ,  $t$ ,  ${}^3\text{He}$ ) and the recoil energy increase (by the additional calls of GEODEN and AMBDEQ) the deposited energy counter at place of an inelastic interaction. Another fraction of the energy released is taken by evaporated neutrons and deexcitation gammas and further transported through the system - escaping or deposited elsewhere. The remaining part of  $E_{ex}$  is lost as the nuclear binding energy. Possible energy depositions contributed by the  $\beta$  deexcitation and by decay of radioactive products are not considered.

The low energy component of absorbed dose obtained from FOLOWN is due to the neutron nuclear reactions (elastic and inelastic scattering,  $(n, \gamma)$  and  $(n, \text{charged})$  capture,  $(n, 2n)$ , fission etc.), contributing to the dose by depositing the kinetic energy of secondary charged particles and the recoil energy of a residual nucleus or fragments in place of a reaction. The corresponding amount of energy is scored in FOLOWN by GEODEN and AMBDEQ after each neutron interaction took place, using the collision density estimate of the neutron fluence multiplied by the relevant kerma factor. The thermal neutron energy is totally absorbed

within one diffusion length calculated for that medium. The energy deposition due to the photons emitted from nuclear deexcitations, inelastic neutron scattering and radiative capture is scored by the EGS module performing their transport.

#### *Dose equivalent*

Estimation of the dose equivalent can be accomplished in FLUNEV by using the two nearly independent methods:

1. By multiplying the absorbed dose in the tissue-equivalent material by quality factors. Each time the energy deposited in the tissue region (note that for other materials this option is not useful) is incremented by one of the contributions described above, the corresponding increment in the dose equivalent is obtained (in AMBDEQ, except of the energy deposited by the electromagnetic cascade which is finally added in EPILOGN with quality factor 1) using a quality factor according to the type and energy of the contributing particle.
2. By multiplying the particle current or fluence (the decision is left to a user in SDUM parameter of BOUNDARY input specification) entering the tissue region by the relevant fluence-to-dose conversion factor. The particles contributing here are the neutrons (in the whole energy range), high energy protons, charged pions and photons; a current of the short-range charged particles is negligible. The respective amount of the dose equivalent is scored by AMBDEQ each time a particle of the type indicated above crosses the specified region boundary from outside.

Estimation of star densities and particle fluences (using the volume tracklength, boundary crossing or collision density methods), accomplished by the original FLUKA subroutine, GEODEN, has not been changed in FLUNEV (except that array dimensions in COMMON /SCORES/, corresponding to the maximum number of detector regions available, have currently been extended to 40). The additional subroutine AMBDEQ, extending the original FLUKA options by calculating the absorbed doses and dose equivalents from different radiation components and for user-selected regions, is called from KASKNEV or FOLOWN, with the following input parameters:

1. IJ - type of the particle: if positive - defined by FLUKA; if negative (for calls from FOLOWN) - a low energy neutron in group -IJ;
2. NREG - current region number; for crossing a boundary - the entered region; the subroutine is active only if the region is included (by input specification) in NRC matrix of COMMON /SAMPLN/;
3. EN - energy of the particle (in GeV);
4. AMOUNT - quantity obtained from the calling subroutine; if positive - to be scored as a boundary-defined estimate (the current and the respective dose equivalent); if negative - to be scored as a volume-defined estimate (the dose absorbed and the dose equivalent by means of quality factor)

Regions of interest are determined as the regions for which the neutron energy thresholds have been set below 50 MeV and for which all the standard scoring options have been required.

(see Section 3). The quality factors and the conversions factors due to ambient dose equivalent [8] are included in DATA statement of AMBDEQ. The histograms of neutron fluences and of the respective dose equivalent spectra for different regions are booked in AMBDEQ by the subroutine HIST of the GEP package. The scored magnitudes, stored in COMMON 'FDSCOR', are finally normalized per incident beam particle, converted to radiation protection units (Gy, Sv) and printed (see Section 5), by the additional subroutine EPITAF called at the end of a run from the new version of EPILOG subroutine, EPILOGN.

### 3 Enhanced user input options in FLUNEV

#### 3.1 Extension of ASSIGNMA option

The new parameter WHAT(6) on the ASSIGNMA card defines the lower energy cutoff (in GeV) for neutron transport in the specified range of geometry regions. Additionally, its negative sign switches on the emission and transport of nuclear gamma rays. If left blank, if set to 0.0 or if set above 0.05 then no the low energy neutron transport subroutine (see Section 2.5) nor the additional estimates (see Section 2.7) are activated. These additional responses and histogram data are scored, printed and stored only for these regions for which the low energy neutron transport option and all 3 flux estimating methods (TRACKLEN, BOUNDARY and COLLISIO) are required by user. Further explanations can be found in Sections 1, 2.5 and 2.7.

#### 3.2 Extensions of START and ENERBINS options

The SDUM parameter on the START card set to 'GEP' character string initializes the interface with GEP graphical package; then further input cards containing specification of histogram bins are immediately required after the START card (see Appendix A as an example).

The SDUM parameter on the ENERBINS card set to 'USERDEF' character string switches on an arbitrary user-defined energy bin structure for the volume tracklength, boundary crossing and collision density estimators. The upper limits (in GeV) of the energy intervals are specified in increasing order as WHAT(i) parameters of the same input card. The first two entries are used to define upper limits of the neutron energy ranges for the extra scoring options for regions defined by the ASSIGNMA, COLLISIO, TRACKLEN and BOUNDARY input commands; if this is desired the third limit should be set to 0.05 GeV.

#### 3.3 Changes of BEAM, BEAMPOS and DUMPTHEM input cards

The first modification concerns sampling source particles from the ring beam shape (useful *e.g.* for the colimator calculations). It is activated by setting the SDUM parameter on the BEAMPOS input card to 'RING'. Then WHAT(4) and WHAT(5) beam width parameters of the BEAM user input card are interpreted as the internal radius of a beam ring and as the radial thickness, instead of the rectangular beam dimensions. WHAT(4)=0 can be used for cylindrical beam shape. Note that the extended subroutine BEAMDV, included in RZGEOM cylindrical geometry module, assumes for that case a beam symmetrical around  $z$  axis.

The second modification enables dumping low energy neutrons on collision tape. WHAT(i) set to 7 causes dump of evaporated neutrons, and WHAT(i) set to 9 causes dump of neutrons slowed down below the energy threshold of high energy module (usually 50 MeV); a negative value activates printout of the dumped variables.

## 4 Additional input data files required by FLUNEV

### 4.1 Evaporation model parameters

*Code input unit:* FT10F001

*Current binary data set name:* D03JMZ.BERTPD

*EBCDIC formatted data set name:* D03JMZ.BERT.EBCDIC

*Retrieval job in member:* #BERDAIN

This file, called the Bertini data tape, contains binary input data for evaporation model (nuclear model parameters), as the nuclear masses, radii, shell and pairing energies, inverse cross sections and pre-computed functions. Since it was taken without any changes from the HETC/KFA code (except that the intranuclear cascade data are skipped), a user interested in contents of the successive data records can be referred to the original documentation [2]. The data are read in by the subroutine BERTTP of the EVAPFLU module, called from the main FLUNEV program. They can be retrieved from the EBCDIC card image format by the job contained in #BERDAIN member of the D03JMZ.FLUNEV.S directory; the binary data are written in the DOUBLE PRECISION mode.

### 4.2 NDEM module nuclear level library

*Code input unit:* FT30F001

*Current binary data set name:* D03JMZ.NDEMLIB.BIN

*EBCDIC formatted data set name:* D03JMZ.NDEMLIB.EBCDIC

*Retrieval job in member:* #TRX

This file contains the nuclear level, shell and pairing energy data, in a version reduced for using only the simplest available physical model of NDEM. The data are read in by the subroutine NDEMFL of the NDEMFLU module, called from the main FLUNEV program. They can be retrieved from the EBCDIC card image format by the job contained in #TRX member of the D03JMZ.NDEM.S directory; the binary data are written in the DOUBLE PRECISION mode.

### 4.3 Multigroup cross section and kerma factor data

*Code input unit:* FT20F001

*Current binary data set name:* D03JMZ.HILO86.MORSEC

*EBCDIC formatted data set name:* D03JMZ.HILO86.EBCDIC

*Retrieval jobs in members:* #MORSECFL, #HILO86B

This file contains the microscopic cross sections and kerma factors, for 45 neutron groups below 50 MeV and 20 photon groups below 20 MeV of HILO, and for 18 isotopes [4]. The original library data in EBCDIC/FIDO format were processed by the job #HILO86B to the binary group-organized set and then by the job #MORSECFL (running the MORSECFLU retrieval code adapted from the corresponding XCHEKR program of the MORSE code system) to the MORSEC package core arrays [3]. Somewhat modified (relative to the original

documentation) arrangement of the data records, containing finally the total cross sections, nonabsorption, gamma emission and downscatter probabilities, scattering angles and kerma factors suitable for MC random walk and estimation, is indicated by comments in the corresponding input subroutine. XSTAPE (called from XSECFL, and this from the main FLUNEV program). The data are read in into a single precision buffer, and then converted to double precision.

The microscopic kerma factors below 20 MeV have been retrieved from the MACKLIB-IV nuclear response library [5] and collapsed to the HILO groups on the IBM/PC-AT computer. Between 20 and 50 MeV the kermas had been derived [7] from the intranuclear -cascade -evaporation model of HETC code. All the used kerma factors have been included in the BLOCK DATA of MORSECFLU code.

## 5 Extensions of FLUNEV code output and using GEP facility

At the end of the input section, external printout is given from XSECFLU module containing the group macroscopic values of total interaction lengths and charged secondary energies for low energy neutrons, for all isotopes and compounds required in a FLUNEV run.

At the end of run, some additional statistics are added concerning the mean results from the evaporation model and from the low energy neutron transport module. The final energy balance table is extended in FLUNEV, and divided into 3 parts:

1. High energy transport process: balance includes primary particle energy, ionisation losses, electromagnetic cascade deposition, excitation energy, escaping particles, neutrons slowed down below 50 MeV and other threshold particles;
2. Evaporation process: balance includes initial excitation energy, energies of evaporated neutrons, protons and heavy fragments, residual excitation energy, recoil energy and energy lost for nuclear binding.
3. Low energy neutron transport: balance includes total energy of neutrons below 50 MeV (should be the sum from threshold and evaporation), energy of charged secondaries (from kermas), and energy absorbed (lost by nonanalog absorption and when slowing down below region dependent threshold, and the energy amount taken by secondary gammas; the rest is assumed to be lost for the excess mass.

All items are averaged over the whole system volume and given per one primary particle, in GeV and percents. Note also that evaporated neutrons and protons are included in the secondary production counters.

The results of the enhanced scoring options (see Section 2.7) are included at the end of FLUNEV printout. For the regions defined by a user (see the note included in description of ASSIGNMA input option, Section 3.1) additionally tabulated are:

1. particle fluences or currents entering a region (if BOUNDARY option specified)
2. dose equivalents estimated by conversion factors (if as above)
3. absorbed doses
4. dose equivalents estimated by the quality factors (valid only if the material in region is tissue)
5. effective quality factors (obtained as the mean ratios of the dose equivalents and the absorbed doses)

versus region number of interest (see Section 3.1 for definition), for the following radiation components:

1. electromagnetic cascade;
2. high energy and evaporated protons;
3. positive pions;



4. negative pions;
5. evaporated heavy fragments and recoils;
6. gamma rays of nuclear origin;
7. neutrons in 5 energy ranges defined optionally to be above 50 MeV, between 50 MeV,  $E_1$ ,  $E_2$  and 0.4 keV and for the thermal group (the limits  $E_1$  and  $E_2$  are specified by user on ENERBINS input card, see Section 3.2).

An example of these additionally scored and printed results can be found in Tab. 7 of our separate report [15].

The subroutine GEPIC is called (if GEP option is specified in START user input card, see Section 3.1) from the main program to initialize the interface with GEP graphical system [10]; subroutines DST1 and DST2 initialize the succeeding destinations (see the list below), BINS2 assign the energy bins of histograms, and GEPW closes the access to GEP (all called from the main program). The energy bin widths are read by GEP after the START card (see example in the Appendix A, and GEP description [10]); currently, the lethargy bins (logarithmic energy) are used for neutrons. The subroutines HIST and CORR of GEP package are called from the KASKNEV and FOLOWN modules, with the first argument being a destination number, the second argument being a logarithm of particle energy, and the third being the booked quantity. The destination numbers and the respective scores correspond to the following histograms of the results:

1. the excitation energies before evaporation (HIST 1); called from KASKNEV ;
2. the evaporated neutron spectrum (HIST 2); called from KASKNEV;
3. the post-evaporation residual atomic mass distribution (HIST 3); called from KASKNEV;
4. the excitation energies versus projectile energies (CORR 4); called from KASKNEV;
5. the secondary neutron yield versus energy and angle (CORR 5); called from KASKNEV if the standard FLUXTYPE input option has the first parameter set to 2;
6. the spectrum of gammas emitted from deexcitations and produced in neutron collisions (HIST 6);
7. the neutron and photon current or dose spectra (HIST 10\*NREG+IDST), where NREG is the region number, IDST is set to 1 for the tracklength estimator, to 2 for the boundary estimator, to 3 for the collision estimator, and to 4 for the dose equivalent; 5 is used for gamma current and 6 for gamma contributions to dose equivalent; called from KASKNEV FOLOWN and AMBDEQ.

The line-printer version of obtained histograms is appended to the job output and additionally written on the special DN data set (see the Appendix A) to be interactively plotted on the laser printer by a user (see Ref. [10], and Figs. 5-9 of our separate report [15], as an example). Bookkeeping of other data desired for plots can be accomplished by including similar calls to GEP subroutines from the source code. To abandon GEP, dummy subroutines can be used instead of the listed above.

## 6 Running FLUNEV code on IBM computers at DESY

### 6.1 Operating system, time and core considerations

FLUNEV (version 1990) is written in FORTRAN77 language, using the IMPLICIT DOUBLE PRECISION specifications in all subprograms, and it is compiled by the FVS compiler. It has been run at the DESY Computer Center on the IBM-3084 and IBM-3090 machines under the MVS/NEWLIB system. The JCL control language cards for a sample problem job are included in the Appendix A.

Usually, only the subroutines changed by a user should be included in input to the compile step; the original versions can be copied from the D03JMZ.FLUNEV90.S source library; the COMMON blocks of FLUNEV and of the standard FLUKA are to be included from FLUNEV90.COMMON and FLUKA90.COMMON. The FLUNEV modules are linked from D03JMZ.FLUNEV90.L load library, previously created by the compiler from the D03JMZ.FLUNEV90.S catalog; the residual modules of original FLUKA are linked from the D03JMZ.FLUKA90.LOAD load library (source version in the catalog D03JMZ.FLUKA90.FORTRAN). The GEPORT cataloged procedure links FLUNEV with the GEP graphical package; besides the standard compile (C), load (L) and go (G) steps it involves the additional P, S, G1 and G2 steps of the FLUNEV job. CERNLIBRARY and DESYLIB subroutines (linked from the R01UTL.CERN.GENLIB, R01UTL.CERN.KERNLIB and SYS1.DESY.LFVS libraries) are occasionally called for a time, date *etc.*; they can be, however, easily abandoned (*e.g.* by calls from the module CERNM2); RNDM2 is the recommended uniform random number generator. The condition codes after the LINKAGE EDITOR step are allowed to be 8, since not all external references (*e.g.* to the EGS code system, to the residual geometry packages, or to the GEP subroutines if not desired) should be satisfied for the particular run. The GEPORT steps S, G1 and G2, saving the results, are additionally protected by the EVEN conditional option from an abnormal failure of the G step.

The execution step requires about 8000 Kb memory (this can be significantly reduced without GEP, EGS, and NDEM and with COMMON /MORSEC/ decreased to include multi-group data for only few elements). The two external binary input data units, 10 and 20 (see Section 4) are used; eventually, another two, unit 8 and 12 for EGS input data, and unit 2 for writing the random number seeds for restart. Except of the printout, the DN output data file contains members with histogram data booked by GEP (see Section 5), and one extra unit 16 (to be earlier allocated by a user) is reserved for storing tabulated results (defined by the user-written subroutine TABDET). Running time and the respective job classes are strongly dependent on the solved problem and the accuracy desired (*e.g.*, setting the neutron lower energy cutoffs in regions, or accomplishing the detailed EGS simulation of electromagnetic cascades), and at DESY computers they vary from 3 minutes to one hour or even more.

## 6.2 Description of a sample problem

The sample problem considered here concerns re-evaluation of the neutron fluences above 0.1 MeV measured at CERN in a calorimeter-like iron structure irradiated by 200 GeV protons from the SPS accelerator. The iron absorber was made of 20 rectangular iron plates of 5 cm thickness. Several kinds of activation detectors and dosimeters were placed in 0.4 cm thick aluminum plates, mounted in 0.7 cm thick slots between the iron layers, and before the first one. Further experimental details are given by Rus *et al.* [14], and comparison of the results calculated by FLUNEV with the measured data can be found in Section 3 of our previous report [17].

The JCL and user input cards for the sample problem are given in the Appendix A of this document. In our calculations the CERN experimental setup was modeled using the cylindrical geometry package (azimutal symmetry of the results was confirmed by the experiment) assuming the transverse diameter of the system to be 30 cm and a rectangular beam profile of 1.2 x 0.9 cm (standard BEAMDV subroutine is linked). The neutron fluences and the absorbed doses were scored by using the volume tracklength method in 30 geometry regions (from the total number of 308) corresponding to the aluminium layers from selected 6 slots (number 0, 1, 4, 8, 15, and 20) divided into 5 radial ranges (up to 1, 3, 6, 10 and 15 cm). The electromagnetic cascade and nuclear gamma energies were accounted for by coupling FLUNEV with NDEM and EGS codes (the required PEGS data for Fe and AL are read in from unit 12). The energy threshold in all the regions of the system was set to 0.1 eV for neutrons, 10 keV for photons and 1 MeV for electrons. The 8 energy intervals for scoring, set between 0, 0.1 (taken optionally, as the transport threshold) 0.8, 3, 6, 15, 25, 35 MeV and beam energy, according to the detector thresholds, are given on ENERBINS card. Additionally, scoring of the neutron and total hadron star densities, and of the total and electromagnetic energy densities is required by the standard FLUKA option.

Following the above problem definition, a 60 minutes job was run on the IBM-3084 computer, handling 28 beam protons and analyzing about 188 inelastic collisions in the whole system per one beam particle. About 3.3 secondary neutrons were emitted per inelastic interaction. The average cpu time for simulating one beam particle history was 12.8 s; this is about 4.5 longer when comparing with the calculation time of original FLUKA code for the same problem, with neutrons transported down to 50 MeV only and with the parametrization of electromagnetic cascade (the time increase factor of 1.7 was observed for the same problem with neutron energy cutoff 0.1 MeV, no nuclear gamma emission and EGS still not linked). The obtained neutron fluences (written on unit 16 by the special version of subroutine TABDET) are tabulated in the Appendix B of this document. Plotted results against the measurements can be found in Figs. 6 and 7, and the spectra histograms in Fig. 8 of our previous report [17].

## Acknowledgments

The FLUNEV code contains parts of the programs, data and concepts developed by others at CERN, ORNL, KFA Jülich, Leipzig University, DESY, Dubna or elsewhere; the author feels indebted to deeply appreciate free exchange of codes, data and ideas between the centers.

Particularly, during development of this version, the original FLUKA code was the subject of continuous revisions and modifications, and the special thanks are due to A.Ferrari from CERN for his frequent aids by current transferring the modified modules and by his professional comments; contacts and discussions with other FLUKA authors (P.A.Aarnio, H.-J.Möhring, J.Ranft, A.Fasso and G.R.Stevenson) have also been extremely valuable. D.Dworak from the Institute of Nuclear Physics, Cracow (Poland) is acknowledged for his solicitous participation in the extension of FLUNEV code for gammas of nuclear origin.

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## Appendixes:

## A JCL and user input cards for the sample job

3

```

/* 08/05/86 002252147 MEMBER NAME #CERNEXP (FLUNEV90) JCL
//DO3JMZ JOB CLASS=L,TIME=(6),NOTIFY=DO3JMZ,MSGLEVEL=(2,1)
//*MAIN LINES=40
/*****
/*          F L U N E V   - 9 0          *
/* FLUKA90 + EGS + EVAP-NDEM (HERMES/KFA) + MORSEC/HILO86 *
/*          COMPILER, LINK & GO JCL, FVS + GEP          *
/* VERSION: FEBRUARY 1990 RUN AT DESY-D3 BY JMZ          *
/*****
/* <= DN FILE IS OUTPUT FROM GEP FOR INTERACTIVE GRAPHICS
// EXEC GEPFORT, DN='DUMMY',
// CPRT='DUMMY',
// LPRM='LET,LIST',
// LPRT='SYSOUT=*',
// LLB1='DO3JMZ.FLUKA90.LOAD',
// LLB2='R01UTL.CERN.GENLIB',
// LLB3='R01UTL.CERN.KERNLIB',
// LLB4='SYS1.DESY.LFVS',
// CPGM=FVS,CRGN=4000K,
// GRGN=8000K,GCND='(8,LT,L)',GTIM='(74)',
// SCND='((8,LT,L),(999,LT,G),EVEN)',
// G1CND='((8,LT,L),(999,LT,G),EVEN)',
// G2CND='((8,LT,L),(999,LT,G),EVEN)'
/* => INCLUDE MODIFIED SOURCE MODULES FOR COMPILATION
//C.SYSIN DD *
.MACRO FLUNEVG
.MACRO &TABDET
/* => INCLUDE COMMON BLOCKS OF FLUKA AND FLUNEV TO SOURCE MODULES
//C.SYSLIB DD DSN=DO3JMZ.FLUKA90.COMMON,DISP=SHR
// DD DSN=DO3JMZ.FLUNEV90.COMMON,DISP=SHR
/* => INCLUDE LOAD MODULES FROM FLUNEV AND FLUKA LIBRARIES
//L.FLUNEV DD DSN=DO3JMZ.FLUNEV90.L,DISP=SHR
//L.SYSIN DD *
INCLUDE FLUNEV (FLUNEVG,KASKNEV,EVAPFLU,XSECFLU,EPILOGN,BLOCKN)
INCLUDE FLUNEV (EVENTQN,NUCREL88,NDEMFLU,EGS4NG,RZGEOM)
INCLUDE SYSLIB (KASKAD,EVENTA,EVENTQ,INTRA)
INCLUDE SYSLIB (BLOCKD,GEOGEO,FLUXES,OUTPUT,NEWOPT,DUMMY)
INCLUDE SYSLIB (EGS4)
ENTRY FLUNEV
//G.FT02F001 DD DUMMY
/* => INCLUDE PEGS4 DATA
//G.FT12F001 DD DSN=DO3JMZ.PEGSDATA.FE200,DISP=SHR

```

<sup>3</sup>See Sections 3-7 of this document for further explanations

```

//          DD DSN=DO3JMZ.PEGSDATA.AL200,DISP=SHR
//G.FT08FOO1 DD DUMMY
//* => INCLUDE DATA FOR EVAPORATION MODEL PARAMETERS (EVAP-HETC/KFA)
//G.FT10FOO1 DD DSN=DO3JMZ.BERTPBD,DISP=SHR
//* => INCLUDE MULTIGROUP NEUTRON CROSS SECTION LIBRARY (HILO86)
//*      NOTE: REAL DATA HAS BEEN WRITTEN IN SINGLE PRECISSION MODE
//G.FT20FOO1 DD DSN=DO3JMZ.HILO86.MORSEC,DISP=SHR
//* => INCLUDE NDEM CODE DATA BASE FOR DEEXCITATION GAMMAS
//G.FT30FOO1 DD DSN=DO3JMZ.NDEMLIB.BIN,DISP=SHR
//* <= OUTPUT DATA WRITTEN BY USER SUBROUTINES
//G.FT16FOO1 DD DSN=DO3JMZ.FLUNEVLA.CERNEGS,DISP=SHR
//* => USER INPUT OPTIONS
//G.SYSIN DD *
TITLE
FLUNEV90 (FLUKA+EVAP+MORSEC) : 200 GEV P ON IRON DUMP, EXP. SETUP, CERN/TIS-RP
COMMENT          1.0
BEAM             -200.0      0.0      0.0      1.2      0.9      1.0PROTON
EGS              0.0        0.0
EGSCUT          0.001      0.00001      0.0      1.0      301.0      1.0
BIAS            0.0        1.0
ASSIGNMA        10.0        2.0      6.0      1.0              -1.0E-10ALUMINUM
ASSIGNMA        11.0        7.0     292.0     15.0              -1.0E-10IRON
ASSIGNMA        11.0        8.0     293.0     15.0              -1.0E-10IRON
ASSIGNMA        11.0        9.0     294.0     15.0              -1.0E-10IRON
ASSIGNMA        11.0       10.0     295.0     15.0              -1.0E-10IRON
ASSIGNMA        11.0       11.0     296.0     15.0              -1.0E-10IRON
ASSIGNMA        10.0       12.0     297.0     15.0              -1.0E-10ALUMINUM
ASSIGNMA        10.0       13.0     298.0     15.0              -1.0E-10ALUMINUM
ASSIGNMA        10.0       14.0     299.0     15.0              -1.0E-10ALUMINUM
ASSIGNMA        10.0       15.0     300.0     15.0              -1.0E-10ALUMINUM
ASSIGNMA        10.0       16.0     301.0     15.0              -1.0E-10ALUMINUM
ASSIGNMA        2.0        17.0     302.0     15.0              VACUUM
ASSIGNMA        2.0        18.0     303.0     15.0              VACUUM
ASSIGNMA        2.0        19.0     304.0     15.0              VACUUM
ASSIGNMA        2.0        20.0     305.0     15.0              VACUUM
ASSIGNMA        2.0        21.0     306.0     15.0              VACUUM
GEOBEGIN        0.0        15.0      15.0      0.0      114.4      50.0R-Z
R-LIMITS        0.0        1.0      3.0      6.0      10.0      15.0
Z-LIMITS        0.0        0.4
Z-LIMITS        5.4        5.8      6.1
Z-LIMITS        11.1       11.5     11.8
Z-LIMITS        16.8       17.2     17.5
Z-LIMITS        22.5       22.9     23.2
Z-LIMITS        28.2       28.6     28.9
Z-LIMITS        33.9       34.3     34.6
Z-LIMITS        39.6       40.0     40.3
Z-LIMITS        45.3       45.7     46.0
Z-LIMITS        51.0       51.4     51.7
Z-LIMITS        56.7       57.1     57.4
Z-LIMITS        62.4       62.8     63.1

```





## B Tabulated results of the sample job

4

FLUNEV90(FLUKA+EGS+EVAP+MORSEC):200 GEV P ON IRON DUMP, EXP. SETUP, CERN/TIS-RP

NEUTRON FLUENCE (CM\*\*-2) IN ENERGY RANGE 0.8 - 15 MEV

SLOT/RAD.:	0 - 1	1 - 3	3 - 6	6 - 10	10 - 15	TOTAL
0.	9.34E-02	4.25E-02	5.39E-02	1.88E-02	7.27E-03	2.16E-01
1.	2.03E-01	1.24E-01	8.85E-02	4.37E-02	2.05E-02	4.80E-01
4.	5.82E-01	3.78E-01	1.97E-01	1.08E-01	5.47E-02	1.32E+00
8.	6.04E-01	5.41E-01	2.85E-01	1.69E-01	7.65E-02	1.68E+00
15.	2.11E-01	2.70E-01	1.64E-01	1.02E-01	4.70E-02	7.93E-01
20.	1.14E-01	6.39E-02	4.19E-02	2.91E-02	1.08E-02	2.60E-01

NEUTRON FLUENCE (CM\*\*-2) IN ENERGY RANGE 3 - 25 MEV

SLOT/RAD.:	0 - 1	1 - 3	3 - 6	6 - 10	10 - 15	TOTAL
0.	1.02E-01	1.50E-02	1.40E-02	3.30E-03	1.68E-03	1.36E-01
1.	1.34E-01	7.84E-02	4.17E-02	2.20E-02	8.41E-03	2.85E-01
4.	3.93E-01	2.30E-01	1.07E-01	4.88E-02	1.65E-02	7.95E-01
8.	4.12E-01	3.03E-01	1.56E-01	7.25E-02	2.51E-02	9.69E-01
15.	1.15E-01	1.37E-01	7.69E-02	4.44E-02	1.68E-02	3.89E-01
20.	1.02E-01	4.48E-02	2.59E-02	1.55E-02	5.92E-03	1.95E-01

NEUTRON FLUENCE (CM\*\*-2) IN ENERGY RANGE 6 - 25 MEV

SLOT/RAD.:	0 - 1	1 - 3	3 - 6	6 - 10	10 - 15	TOTAL
0.	7.89E-02	1.36E-02	4.99E-03	2.47E-03	1.01E-03	1.01E-01
1.	1.17E-01	6.09E-02	2.51E-02	1.34E-02	4.43E-03	2.21E-01
4.	3.03E-01	1.58E-01	7.33E-02	2.85E-02	9.33E-03	5.72E-01
8.	2.87E-01	2.11E-01	1.05E-01	4.51E-02	1.74E-02	6.65E-01
15.	1.02E-01	1.05E-01	4.59E-02	3.34E-02	1.10E-02	2.98E-01
20.	3.86E-02	3.00E-02	1.69E-02	1.07E-02	4.89E-03	1.01E-01

NEUTRON FLUENCE (CM\*\*-2) IN ENERGY RANGE 35 - 200 MEV

SLOT/RAD.:	0 - 1	1 - 3	3 - 6	6 - 10	10 - 15	TOTAL
0.	3.33E-01	9.61E-03	4.28E-03	3.16E-03	1.60E-03	3.51E-01
1.	1.33E+00	7.99E-02	1.72E-02	3.70E-03	2.99E-03	1.44E+00
4.	2.35E+00	3.26E-01	8.16E-02	2.81E-02	6.28E-03	2.79E+00
8.	1.78E+00	4.85E-01	1.24E-01	4.76E-02	1.47E-02	2.45E+00
15.	5.73E-01	2.52E-01	1.02E-01	3.60E-02	1.81E-02	9.81E-01
20.	2.68E-01	1.47E-01	4.97E-02	2.01E-02	7.21E-03	4.93E-01

<sup>4</sup>See Section 7 of this document for problem description

## C Contents of members in the source directory

FLUNEV modules (D03JMZ.FLUNEV90.S):

&&INFO	text containing short information
&TABDET	special output subroutine storing results on unit 16
#BERDAIN	retrieval job for Bertini data tape
#CERNEXP	job control and user input cards for sample problem
#CERNEGS	job control and user input for sample problem, with EGS
#VFORTCL	the same job, but without GEP interface
#HILO86B	retrieval job for HILO86 library(binary from FIDO)
#MORSECF	retrieval job for MORSEC organized cross section data
@FLUNCOM	new COMMON blocks to be included in VS FORTRAN source
BLOCKN	modified BLOCK DATA module of FLUKA
EGS4NG	modified EGSLNK and AUSGAB subroutines of EGS, nuc. gamma
EPILOGN	modified PROLOG,EPILOG and new EPITAF and AMBDEQ routines
EVAPFLU	evaporation module
EVENTQN	modified procedures of EVENTQ inelastic collision module
FLUNEVG	modified main program of FLUNEV
KASKNEV	modified KASKAD and new FOLOWN subroutines
MORSECFL	source code processing HILO data to MORSEC format
NDEMFLU	NDEM module for gamma deexcitations
NUCREL88	elastic interaction module (version of H.-J.Moehring)
RZGEOM	cylindrical geometry module
XSECFLU	low energy n and gamma cross section and collision module

FLUNEV COMMON blocks (D03JMZ.FLUNEV90.COMMON):

AADAT,CONTLN,CORINC,DEFMAT,EBISCO,EVASCO,EVA1,FDSCOR,HETC5,SEED,HETC7,  
HETTP,LABCOS,LOCSIG,LOCKSEC,MACSIG,MORSEC,RUNTIT,SAMPLN,GAMNUC

Remaining FLUKA modules (D03JMZ.FLUKA90.FORTRAN):

BLOCKD,CARGEO,CERNM2,COMGEO,DUMMY,EGS4,EVENTA,EVENTQ,FLUXES,GEOGEO,INTRA  
KASKAD,MAIN,NEOPT,OUTPUT,RTHGEO,RZGEO

FLUKA COMMON blocks (D03JMZ.FLUKA90.COMMON):

AACOLL,ACRACY,AUXPAR,BAMJCM,BEAM,BEMIT,BIASLP,BLNKCM,BLNKDM,BOUNDS,  
BREMPPR,CALOR,CARBOU,CARSEC,CASLIM,CMSRES,COMCON,COMSEC,COUNT,COUNTQ,  
DECAYC,DECAYC2,DETECT,DETLOC,DLTADP,DMPTAP,EGSTCK,ELECIN,EMSHO,EPCONT,  
EPISOR,ERRGEO,ERRGE2,ESTSUM,EVESEL,FAULTX,FINLSP,FINLSP2,FINLSP3,FINPAR,  
FINPAR2,FINUC,FINUC2,FLUXES,FXTMX,FXTMX1,GEOSEL,HADPAR,INPDAT,LANDAU,  
MAGPAR,MAPA,MAPA2,MEDIA,MEDIAC,METLSP,MISC,MULTS,NUCPAR,PAPROP,PART,  
PART2,PART3,PATHCM,PHOTIN,PLOPRI,QDEBUG,RANDOM,RRCON,RTHBOU,RTHSEC,  
RZBOU,RZSEC,SCORES,STACK,STARS,STCKA,THR,THRESH,UPHIIN,UPHIOT,USEFUL,

