ИНСТИТУТ ЯДЕРНОЙ ФИЗИКИ
им. Г.И. Будкера СО РАН

Budker Institute of Nuclear Physics

A.D. Bukin, N.A. Grozina, V.N. Ivanchenko
K. Hänßgen

UNIMOD2 – THE UNIVERSAL MONTE CARLO CODE.

4. SIMULATION OF HADRON-NUCLEUS INTERACTIONS WITH THE NUC92 CODE

BUDKERINP 92-93

НОВОСИБИРСК

UNIMOD2—The universal Monte Carlo code.
4. Simulation of hadron-nucleus interactions with the NUC92 code.

A. D. Bukin, N. A. Grozina, V. N. Ivanchenko

Budker Institute of Nuclear Physics,
630090 Novosibirsk 90, Russia

K. Hänßgen

Leipzig University, Physics department, WBHEP 0–7010,
Leipzig, Augustnsplatz, Germany

ABSTRACT

The NUC92 code for simulation of hadron-nucleus interactions is presented. Its interface with the UNIMOD2 Monte Carlo code and algorithms of the program are briefly described. Example applications and comparison with experimental data are discussed.

1 Introduction

Simulation of hadron interactions with nuclei is one of the most difficult and ambiguous problems of the detector simulation. The main difficulties are connected with the absence of a complete and accurate theory describing all phenomena arising at hadron-nucleus collisions and incompleteness of the experimental data. Henceforth, simplified models of interactions are necessary, but the accuracy of possible testing of a model is determined by concrete experimental possibilities to check independently Monte Carlo results. One should choose an appropriate simulation program depending on the goals of an experiment.

The nuclear cascade simulation program NUCRIN [1] was used in the program UNIMOD [2] for several years; now it is incorporated into the program GEANT [3] as a generator of hadron-nucleus interactions in the hadron momentum range (0.1–5) GeV. The NUCRIN algorithm separates a single two-particle interaction of an incident hadron with a nucleon and a nuclear cascade described phenomenologically.

The main advantage of NUCRIN is its compactness and time efficiency. This results from using approximate final proton and neutron spectra from nuclear cascades and nuclear excitation spectra. They were constructed by the authors of NUCRIN using a much more comprehensive program HADCAS [4] for a detailed nuclear cascades' simulation. The comparison of NUCRIN Monte Carlo results with data of e^+e^- experiments at Novosibirsk demonstrated a good agreement as a whole [5]. It was estimated in the Neutral Detector experiment that the accuracy of such simulation is about 10% [6]. However,

NUCRIN has some disadvantages. Secondary hadron-nucleus interactions are not taken into account, and hence the phenomena like π or K absorption can't be simulated adequately. The NUCRIN model appears to be rather rough at small momenta of incident hadrons. (< 0.3 GeV). And also, a user has no possibility to access parameters of the program, he can't put corrections corresponding to a specific experiment.

The old version of NUCRIN was essentially modified for use in the new universal Monte Carlo code UNIMOD2 [7] being developed at Novosibirsk. The authors concentrated on two points. First, an access to simulation parameters and data bases of particle properties and of hadron-nucleus interactions has been made easier for a user. Second, an algorithm of simulation of very soft hadrons has been essentially modified. A possibility to simulate an elastic hadron-nucleus scattering (using the program NUCREL [8]), and a capture of stopped μ^-, π^-, K^-, $\bar{p}$ by a nucleus, was also included. The resulting code is called NUC92. The main modifications of the standard version NUCRIN made in NUC92 will be briefly described below.

2 Data input

Data on particle properties and hadron-nucleus reaction cross sections in the NUCRIN code were located in a BLOCK DATA, and hence were practically inaccessible for a user. In the program NUC92, the particle properties and the reaction parameters are read from formatted text files with the fixed names PARTICLE.DAT and REACCHAN.DAT. A user can prepare original versions of these files. The data on the total cross sections remain in the BLOCK DATA. Only the possibility to scale all total cross sections by a constant has been included. A user can also access the basic simulation parameters (using the program UM1375): a cut on the kinetic energy of an incident hadron; a cut on the kinetic energy of final neutrons; a fraction of the nucleus excitation energy (i. e. the total energy of soft products) being transformed to the local ionization; a root-mean-square deviation of the last quantity.

3 Simulation of the soft hadron interactions

One of the problems of the NUCRIN code is that it is not suited for simulation of very soft hadrons with the kinetic energy 0–100 MeV. NUCRIN provides two alternatives to deal with this case. Either the incident hadron is absorbed and all its energy is transformed into the nuclear excitation energy, or two-

particle interactions are simulated. Such a simulation is not accurate at low energies, and takes a lot of CPU time due to the Pauli principle limitations.

This problem has been solved in NUC92 by special programs to simulate a capture of soft negatively charged particles. The basic algorithm of generation of secondary particles has been modified: if the energy of an incident hadron appears to be below a given cut, then this energy is transferred to the nuclear excitation energy for a cascade simulation, and the incident hadron with zero kinetic energy is put to the final particle list. This solves the problem of inefficiency of the NUCRIN algorithm for very soft particles. The program UNIMOD2 accepts the final particle list from NUC92 and ensures the simulation of decays of positively charged particles and the capture of negatively charged ones.

The possibility of multiple interactions of soft hadrons has been also included. To this end, the energy of an incident hadron is incremented by the potential well depth before the simulation of a hadron-nucleus interaction. The energies of secondary particles are decremented by the same amount at the end of simulation of a single interaction. The proton and neutron Fermi levels are taken at 8 MeV below zero level for all nuclei. The potential well depth for all other hadrons is 30 MeV.

If a particle produced in an interaction appears to be below the threshold of escaping the well and it is not pion, K^0, or $\bar{K}^0$, it is considered stopped. The nucleons are excluded from the cascade, their energy is included to the excitation energy. Other types of hadrons are added to the final particle list with zero kinetic energy.

If a secondary pion appears to be trapped inside the potential well, it is considered absorbed. The most probable mechanism of pion absorption is πnp-interaction [9]. Therefore the pion energy and charge are transferred to the np-pair at rest. The escaping of these nucleons from the nucleus is then simulated. Thus, the possibility to simulate the pion absorption is introduced in NUC92 which was absent in NUCRIN.

If a secondary K^0 or $\bar{K}^0$ appears to be trapped inside the potential well, they are considered captured. A secondary interaction of a captured neutral kaon with nucleons is then simulated. The current algorithm assumes that K^0 is transformed to K^+ or K_s with equal probabilities, while an $\bar{K}^0$ interaction with a nucleon produces one of the final states listed in the Table 1. The probabilities of these reactions are obtained from the cross section data base of NUCRIN.

Table 1: Interaction of a captured $\bar{K}^0$ with nucleons.

initial state	final state	probability (%)
$\bar{K}^0 + n$	$p + K^-$	34.0
	$\Lambda^0 + \pi^0$	2.9
	$\Sigma^+ + \pi^-$	8.2
	$\Sigma^- + \pi^+$	6.8
	$\Sigma^0 + \pi^0$	5.3
$\bar{K}^0 + p$	$\Lambda^0 + \pi^+$	24.7
	$\Sigma^0 + \pi^+$	9.9
	$\Sigma^- + \pi^0$	8.2

4 Simulation of the π^- capture by a nucleus

The process of π^- absorption by atomic nuclei is sufficiently well investigated [9, 10]. The model [11] preserving main features of the process is used for simulation. This model includes three stages: the primary pion absorption, the intranuclear cascade and the thermal neutron emission.

The primary pion absorption can proceed as $\pi^- + pn \to nn$ or $\pi^- + pp \to pn$. The probability of the second process is

$$P(\pi^- + pp) = \frac{Z-1}{R(A-1)+Z-1}, \qquad (1)$$

where R is a model parameter. We use the value $R = 3$ obtained from experiments with nuclei having $A > 30$ [9].

The total energy of the nucleon pair is simulated with the account of the initial pion energy and the Fermi motion in the nucleus. A nucleon with a positive energy can escape from the nucleus. If it haven't escaped, it collides with one of the non-excited nucleons producing one more excited nucleon and a hole.

The intranuclear cascade is simulated using the hybrid exciton model [11]. The energy of an excited nucleon is first generated, and its escape probability is calculated. If it has escaped, the nuclear excitation energy and the number of excited nucleons is decremented; if not—one more excited nucleon and a hole appear.

After the cascade has finished, a highly excited nucleus remains, which will evaporate particles. The main deexcitation mechanism is the neutron emission, because the proton emission is suppressed by the Coulomb barrier.

Table 2: Neutron multiplicity as a function of the cutoff energy. First line—Monte Carlo, second line—experiment.

Element	$E > 0$	$E > 3$	$E > 5$	$E > 10$	$E > 20$	$E > 40$
^{12}C	1.88	1.55	1.41	1.25	1.105	0.82
		1.77(27)	1.66(25)	1.46(22)	1.21(18)	0.83(12)
^{59}Co	4.15	2.36	1.64	1.16	0.97	0.71
		2.25(34)	1.91(29)	1.36(20)	1.03(15)	0.69(11)
^{197}Au	6.60	3.19	1.85	1.04	0.88	0.603
		2.82(42)	2.80(31)	1.26(91)	0.90(14)	0.56(8)

The nucleus can also emit gamma-quanta, but this is not taken into account in the current program, as well as the nuclear fussion.

The thermal neutron spectrum is supposed to be

$$W(E) = Ee^{-E/\theta}, \qquad (2)$$

where the nucleus temperature θ is supposed to be constant equal to 1.4 MeV. The neutron multiplicity is determined by A and the excitation energy [11].

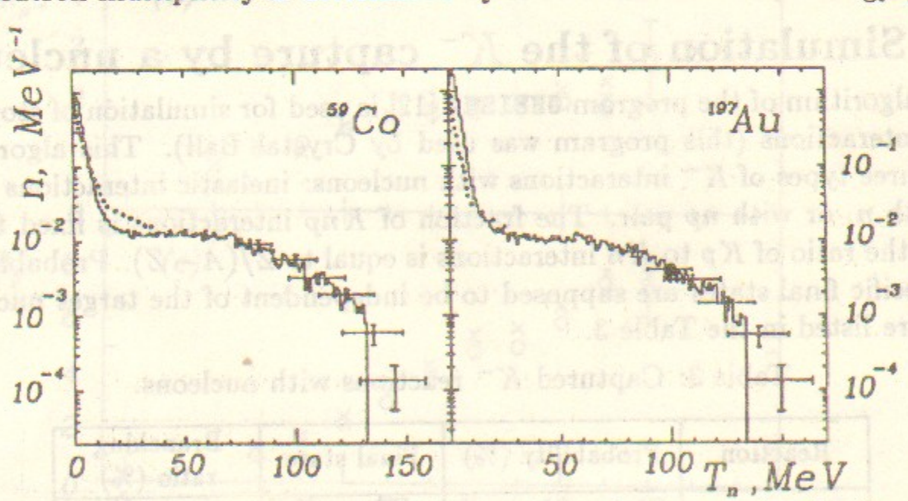

Fig. 1. Neutron spectra at the π^- absorption at rest by the Co and Au nuclei.

Fig. 1 shows the neutron spectra at the π^- absorption at rest by the Co and Au nuclei. The characteristic features of spectra related to its cascade and evaporation parts are clearly seen. Because of the surface character of the primary absorption, the high energy part of the spectrum is nearly independent of the target nucleus atomic number both in the size and the shape.

Fig. 2 shows the similar proton spectra. The growth of the neutron multiplicity demonstrates a strong dependence of the multiplicity of evaporated neutrons on the target nucleus mass, see Table 2.

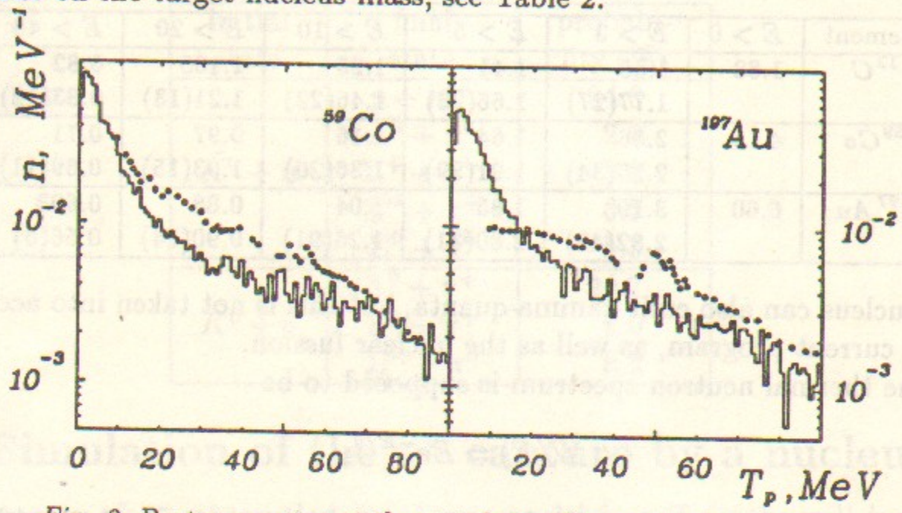

Fig. 2. Proton spectra at the π^- absorption at rest by the *Co* and *Au* nuclei.

5 Simulation of the K^- capture by a nucleus

The algorithm of the program GHEISHA [12] is used for simulation of stopped K^- interactions (this program was used by Crystal Ball). This algorithm has three types of K^- interactions with nucleons: inelastic interactions with p, with n, or with np pair. The fraction of Knp interactions is fixed to be 20%; the ratio of Kp to Kn interactions is equal to $Z/(A-Z)$. Probabilities of specific final states are supposed to be independent of the target nucleus, and are listed in the Table 3.

Table 3: Captured K^- reactions with nucleons.

Reaction	Probability (%)	Final state	Branching ratio (%)
$K^- + p$	$0.80Z/A$	$\Sigma^+ + \pi^-$	22
		$\Sigma^0 + \pi^0$	28
		$\Sigma^- + \pi^+$	44
		$\Lambda^0 + \pi^0$	6
$K^- + n$	$0.80(A-Z)/A$	$\Sigma^0 + \pi^-$	30
		$\Sigma^- + \pi^0$	30
		$\Lambda^0 + \pi^-$	40
$K^- + n + p$	0.20	$\Sigma^0 + n$	50
		$\Sigma^- + p$	50

6 Simulation of the $\bar{p}$ capture

The model [13] is used for simulation of the annihilation of $\bar{p}$ at rest on a nucleus. It is a simplified version of the intranuclear cascade model. The simulation consists of two stages. On the first stage, $\bar{p}$ interacts with p or n (the probabilities are proportional to their numbers). They produce from 3 to 7 pions with the probabilities obtained from experiment. Their momenta are generated uniformly distributed over the phase space.

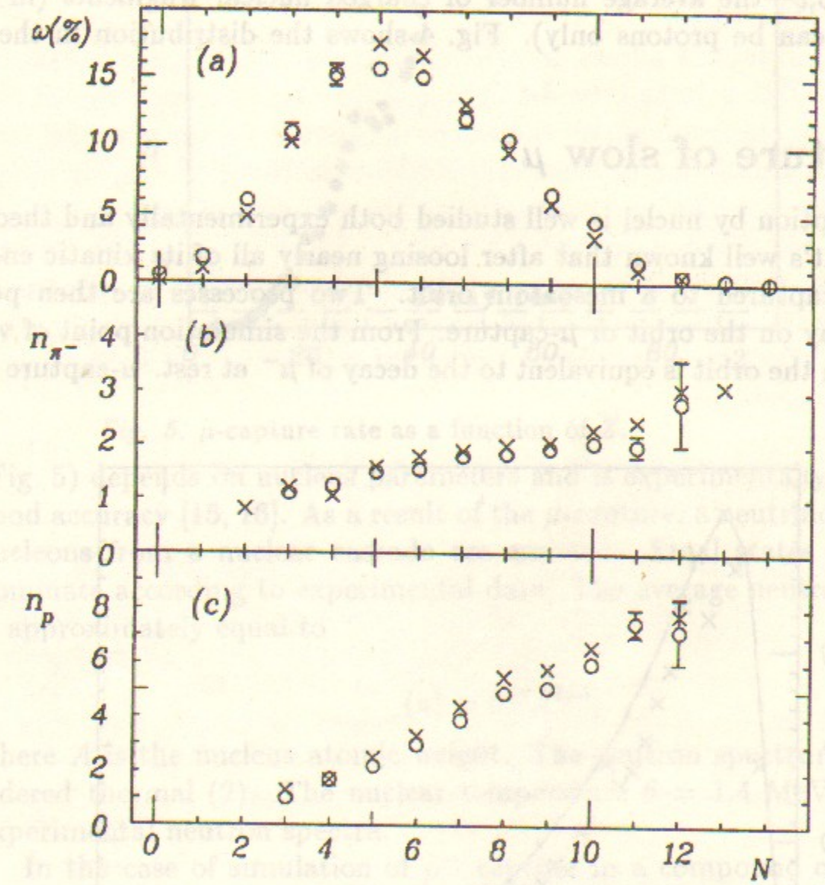

Fig. 3. $\bar{p}$ annihilation on *Ne* at rest. Circles—LEAR experimental data, crosses—Monte Carlo results: *a*) the distribution in the multiplicity of charged particles; *b*) the average number of π^- as a function of the multiplicity of charged particles; *c*) the average number of charged nuclear fragments.

Each pion either enters the nucleus and produces a cascade (with the probability 60%), or doesn't interact with it. The number of interactions of each pion is generated from the Poisson distribution. The pion-nucleon scattering is supposed to proceed via the Δ resonance. The last pion interaction with some probability is absorption: $\pi N \to \Delta$, $\Delta N \to NN$.

This model was compared to the LEAR experimental data for Ne [14]. Fig. 3,*a* shows the distribution in the multiplicity of charged particles; Fig. 3,*b*—the average number of π^- as a function of the multiplicity of charged particles; Fig. 3,*c*—the average number of charged nuclear fragments (in this model they can be protons only). Fig. 4 shows the distribution in the π^- momentum.

7 Capture of slow μ^-

Muon absorption by nuclei is well studied both experimentally and theoretically [15]. It's well known that after loosing nearly all of its kinatic energy a muon is captured to a mesoatom orbit. Two processes are then possible: μ^- decay on the orbit or μ-capture. From the simulation point of view, the decay on the orbit is equivalent to the decay of μ^- at rest. μ-capture rate

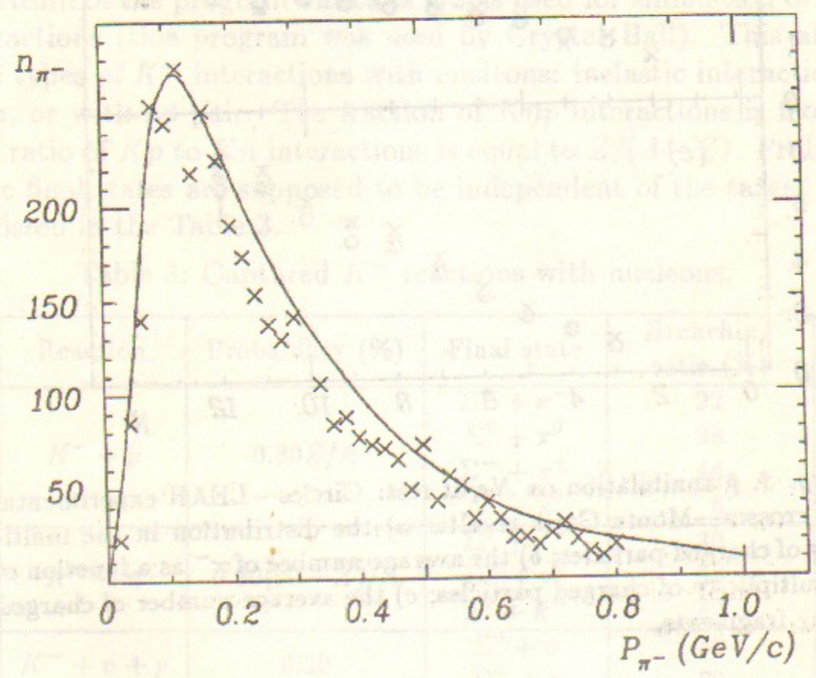

Fig. 4. The distribution in the π^- momentum.

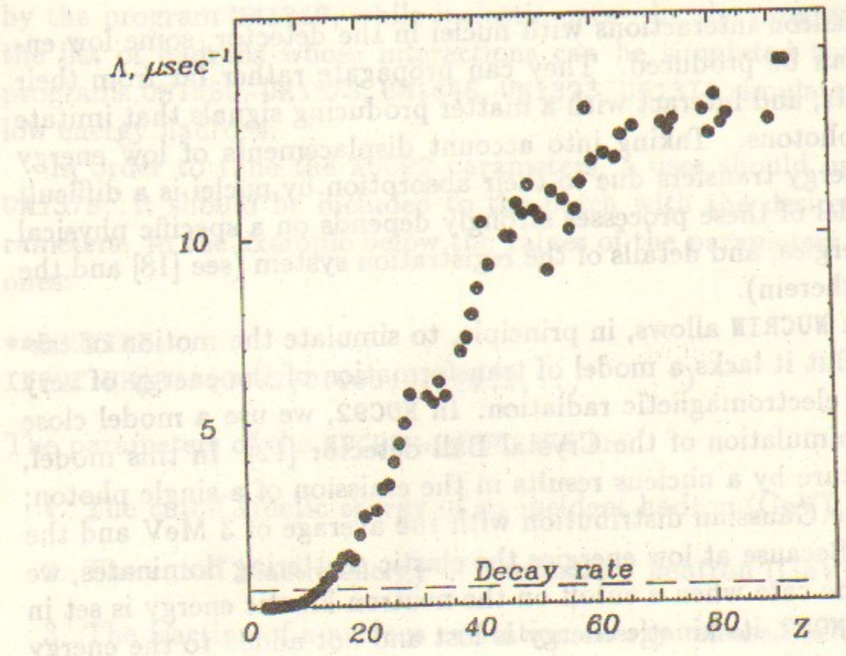

Fig. 5. μ-capture rate as a function of Z.

(Fig. 5) depends on nucleus parameters and is experimentally known with a good accuracy [15, 16]. As a result of the μ-capture, a neutrino and probably nucleons from a nuclear cascade are emitted. Final states with neutrons dominate according to experimental data. The average neutron multiplicity is approximately equal to

$$\langle n \rangle = 0.3A^{1/3}, \qquad (3)$$

where A is the nucleus atomic weight. The neutron spectrum may be considered thermal (2). The nuclear temperature $\theta = 1.4$ MeV, according to experimental neutron spectra.

In the case of simulation of μ^- capture in a compound or mixture, it's necessary to choose which atom captures the μ^-. The program chooses two types of atoms giving main contributions to the density of the compound. If their atomic numbers are Z_1 and Z_2, then the ratio of probabilities of μ^- capture is supposed to be Z_1/Z_2. There exist rather accurate measurements of these probabilities for metal-galogen compounds (NaI, CsI) [17]. Therefore in a particular case when the first of the two atoms in the compound is I we use the phenomenological relation for the ratio of the capture probabilities $0.66Z_1/Z_2$.

8 Absorption of low energy neutrons

As a result of hadron interactions with nuclei in the detector, some low energy neutrons can be produced. They can propagate rather far from their production points, and interact with a matter producing signals that imitate signals of soft photons. Taking into account displacements of low energy neutrons and energy transfers due to their absorption by nuclei is a difficult problem. A model of these processes strongly depends on a specific physical task, hadron energies, and details of the registration system (see [18] and the literature cited therein).

The program `NUCRIN` allows, in principle, to simulate the motion of cascade particles. But it lacks a model of transformation of the energy of very soft neutrons to electromagnetic radiation. In `NUC92`, we use a model close to one used for simulation of the Crystal Ball detector [12]. In this model, the neutron capture by a nucleus results in the emission of a single photon; its energy has the Gaussian distribution with the average of 3 MeV and the width 1.5 MeV. Because at low energies the elastic scattering dominates, we assume that in the case when a cutoff on the neutron kinetic energy is set in the program `UNIMOD2`, its kinetic energy is lost and not added to the energy of the emitted photon.

9 Instructions for a user of UNIMOD2

A complete `UNIMOD2` user guide can be found in [7], therefore here we discuss only methods of including `NUC92`. The `NUC92` code is implemented in IBM-VM and VAX-VMS systems. In both cases it is included to the file containing the standard list of particle-matter interactions (`STNINTR2`). A VAX-VMS user should assign the name `NUCD` to the directory containing data files for `NUC92` (using the `ASSIGN` command). This assignment may be made in the `LOGIN.COM` file or separately. If the standard data files are used, then the command is

```
ASSIGN DISK$D1:[UNIMOD] NUCD
```

If a user uses his original interaction list, then in both systems it is necessory to include the following lines to the input file in order to include `NUC92`:

```
**ROUTINE
PROCESS:
UM1316(PI+,PI-,K+,K-,KO/S,KO/L,PROTON,NEUTRON,A/PROTON,A/NEUTRON)
UM1371(PI+,PI-,K+,K-,KO/S,KO/L,PROTON,NEUTRON,A/PROTON,A/NEUTRON)
SPECEND:UM1650(PI-),UM1373(K-),UM1645(A/PROTON),UM1323(MU-)
SPECEND:UM1378(NEUTRON)
```


These lines declare that elastic hadron-nucleus interactions are simulated by the program `UM1316`, while inelastic ones—by the program `UM1371`, and the list of hadrons whose interactions can be simulated is specified. The programs `UM1650`, `UM1373`, `UM1645`, `UM1323`, `UM1378` simulate the capture of low energy hadrons.

In order to tune the `NUC92` parameters, a user should use the program `UM1375`. It should be included to the batch with the desired values of parameters. In the example below the values of the parameters are the default ones:

```
**ROUTINE
INPUT:UM1375(0.02,0.005,0.3,0.2,1.,'    ')
```

The parameters of the `NUC92` and `UM1375` are:

1. The cutoff kinetic energy of an incident hadron (GeV);
2. The cutoff kinetic energy of a secondary neutron (GeV);
3. The fraction of a nucleus excitation energy released as an ionization in the interaction point;
4. The root-mean-square deviation of the above quantity;
5. The factor by which all total cross sections are scaled as compared with the values from the `NUC92` data base in the current job;
6. (`CHARACTER*4`)—If it is equal to `TEST`, then the files with particle properties and reaction channels are printed.

10 Examples

Fig. 6 shows the results of simulation of pions in the NaI calorimeter of the SND detector [19]. The energy deposited by charged particles in a cluster was normalized to the incident pion energy. The ionization losses peak of the pion that have not interacted with nuclei is clearly seen in all hystograms. The significant second peak for 200 MeV π^+ is related to the registration of the energy deposited by μ^+ and e^+ produced in the stopped π^+ decays. The heights of this peak is determined by the time of integration of the ADC signal, in this case it is 3μsec.

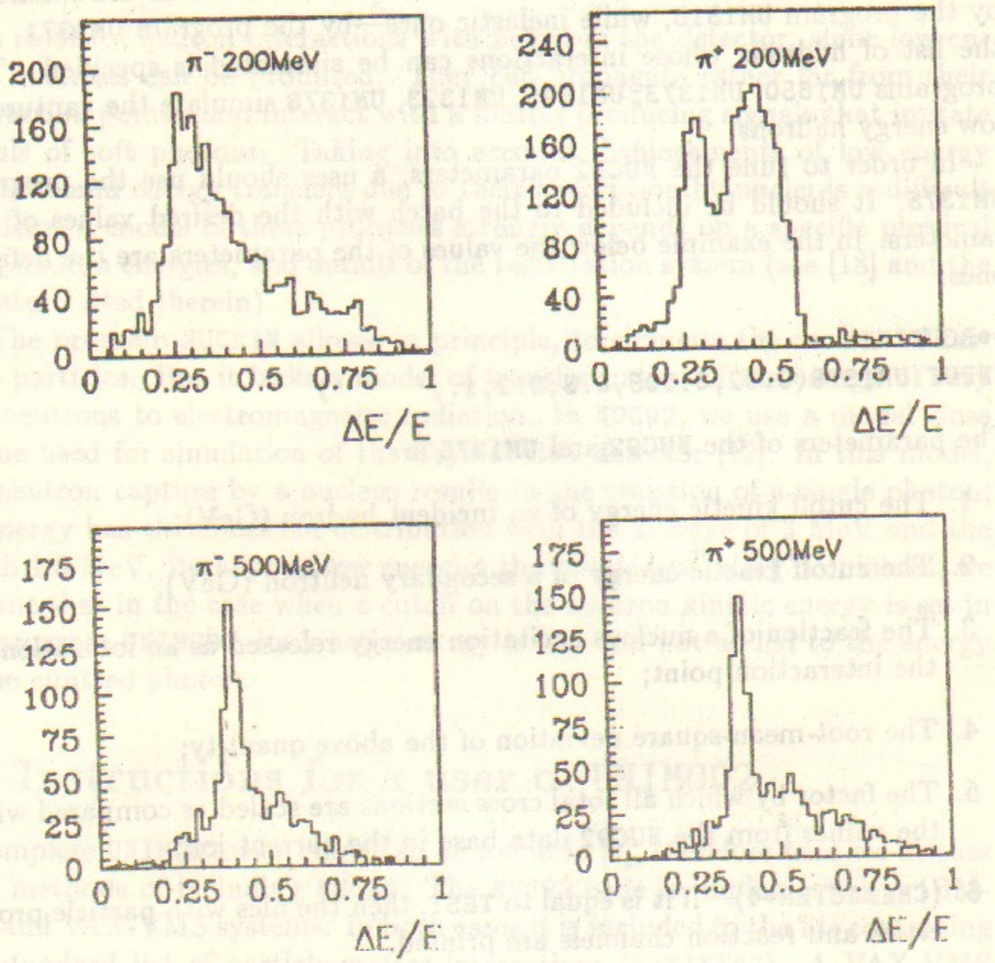

Fig. 6. The spectra of energy deposited by pions in the NaI calorimeter of the SND detector.

Fig. 7 shows the distribution in the energy deposited by K_L in the CsI wall (size 50 × 50 × 15cm) imitating the calorimeter of the CMD-2 detector [20]. Incident K_L fly perpendicularly to the calorimeter to its center. The probability of the signal with the 10 MeV threshold for such a calorimeter appeared to be $(38.0 \pm 0.6)\%$.

These results demonstrate the applicability of the `NUC92` code at low hadron energies and allow to improve the simulation in future.

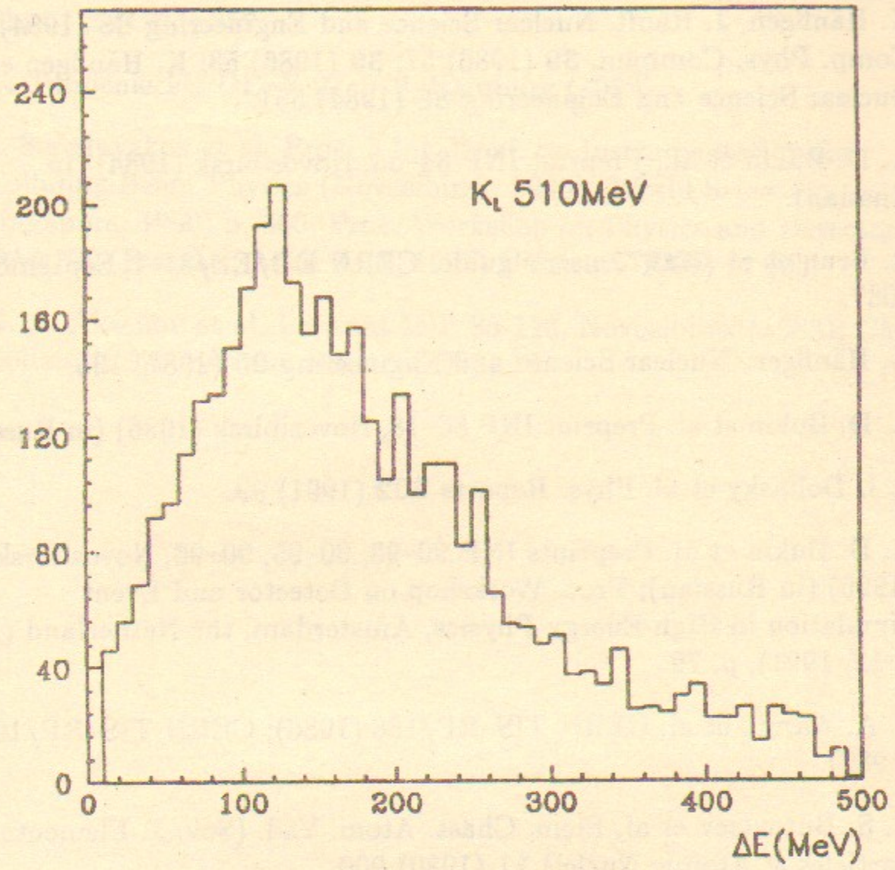

Fig. 7. The spectra of energy deposited by K_L in the CsI calorimeter of the CMD-2 detector.

References

[1] K. Hänßgen, J. Ranft. Nuclear Science and Engineering **88** (1984) 537; Comp. Phys. Commun. **39** (1986) 37; **39** (1986) 53; K. Hänßgen et al., Nuclear Science and Engineering **88** (1984) 551.

[2] A. D. Bukin et al., Preprint INP 84–33, Novosibirsk (1984) (in Russian).

[3] R. Brun et al. **GEANT3** user's guide. CERN DD/EE/84–1, September 1987.

[4] K. Hänßgen. Nuclear Science and Engineering **95** (1987) 135.

[5] A. D. Bukin et al. Preprint INP 86–18, Novosibirsk (1986) (in Russian).

[6] S. I. Dolinsky et al. Phys. Reports **202** (1991) 99.

[7] A. D. Bukin et al. Preprints INP 90–93, 90–95, 90–96, Novosibirsk (1990) (in Russian); Proc. Workshop on Detector and Event Simulation in High Energy Physics, Amsterdam, the Netherland (April 8–12, 1991), p. 79.

[8] P. A. Aarnio et al. CERN TIS–RP/168 (1986); CERN TIS–RP/190 (1987).

[9] V. S. Butovtsev et al. Elem. Chast. Atom. Yad. (Sov. J. Elementary Particles & Atomic Nuclei) **11** (1980) 900.

[10] H. P. Isaak et al. HPA **55** (1982) 477.

[11] Y. K. Lee. Phys. Rev. **C33** (1986) 1707.

[12] Z. Jakubowsky, M. Kobel. DESY 89–165, Hamburg (1989).

[13] N. A. Grozina. Preprint INP 90–145, Novosibirsk (1990) (in Russian).

[14] F. Balestra et al. Nucl. Phys. **A491** (1989) 541.

[15] V. V. Balashov, G. Ya. Korenman, R. A. Eramzhan. Meson absorption by atomic nuclei. Atomizdat, Moscow (1978).

[16] J. C. Sens. Phys. Rev. **113** (1959) 679; M. Eckhause et al. Nucl. Phys. **81** (1966) 575.

[17] V. G. Zinov, A. D. Konin, A. I. Mukhin. Yad. Fiz. (Sov. J. Nucl. Phys.) **2** (1965) 859.

[18] T. Tumieniecka. DESY 91–012, Hamburg (1991).

[19] S. Serednyakov et al. Proc. 5 Int. Conf. on Instrumentation for Colliding Beam Physics (Novosibirsk, 1990) (World Scientific, Singapore, 1990) p. 360; Proc. Workshop on Physics and Detectors for DAΦNE (Frascati, April 9–12, 1991) (Frascati, 1991) p. 605.

[20] G. A. Aksenov et al. Preprint INP 85-116, Novosibirsk (1985); CMD-2 Collab. ICFA Instrum. Bull. **5** (1988) 18.