SIMULATION OF HADRONIC INTERACTIONS IN THE FRAMEWORK OF THE RTS&T-2017 CODE

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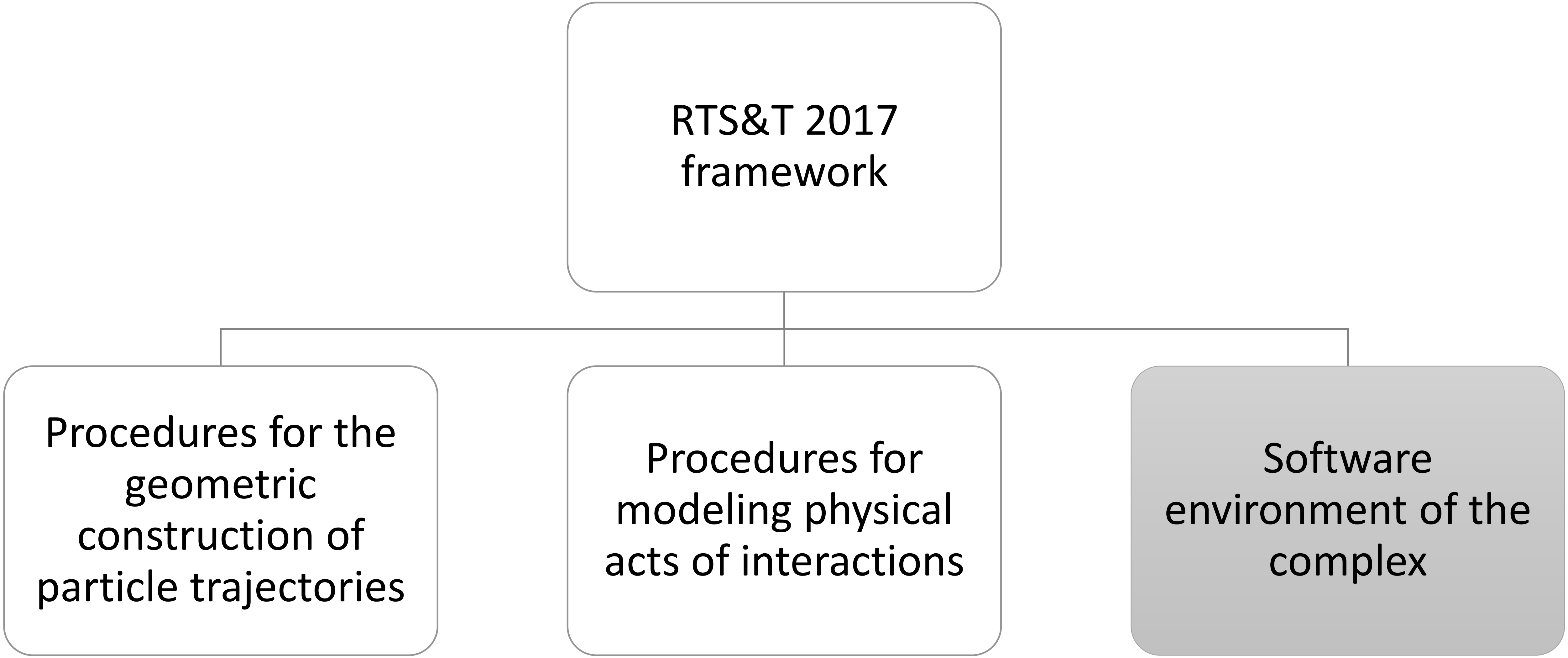
Report structure

- INTRODUCTION
- General information about RTS&T 2017
- Hadron generators models in package RTS&T 2017
  - TDM - Theory-driven models
  - PDM - Parameterization-Driven Model
  - Data-driven models
- Energy ranges in package RTS&T 2017
  - High energy range
  - Intermediate energy range
  - Low energy range
- SUMMARY
- REFERENCES

Architecture of the RTS&T 2017 framework

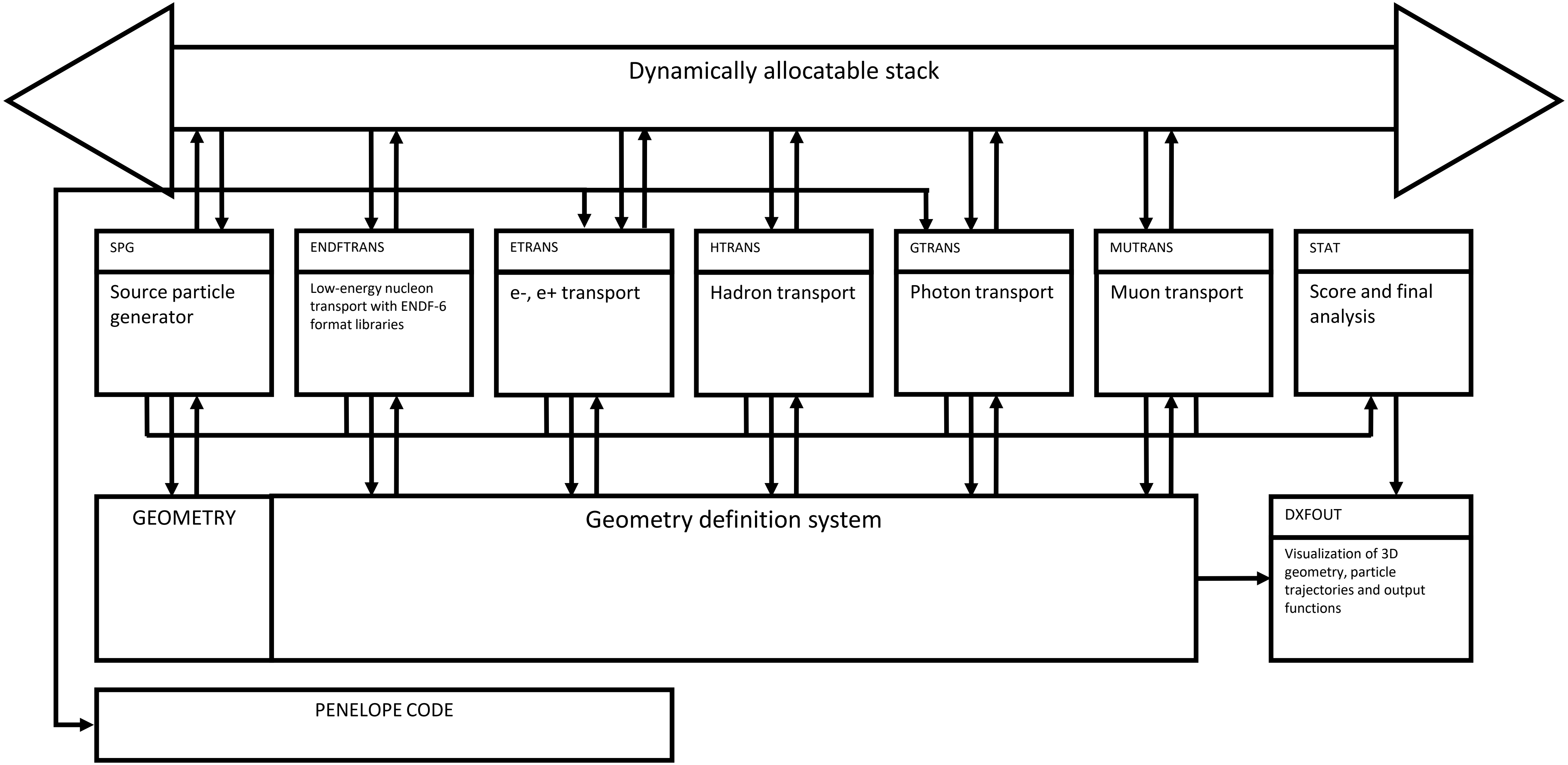


Architecture of the RTS&T 2017 framework

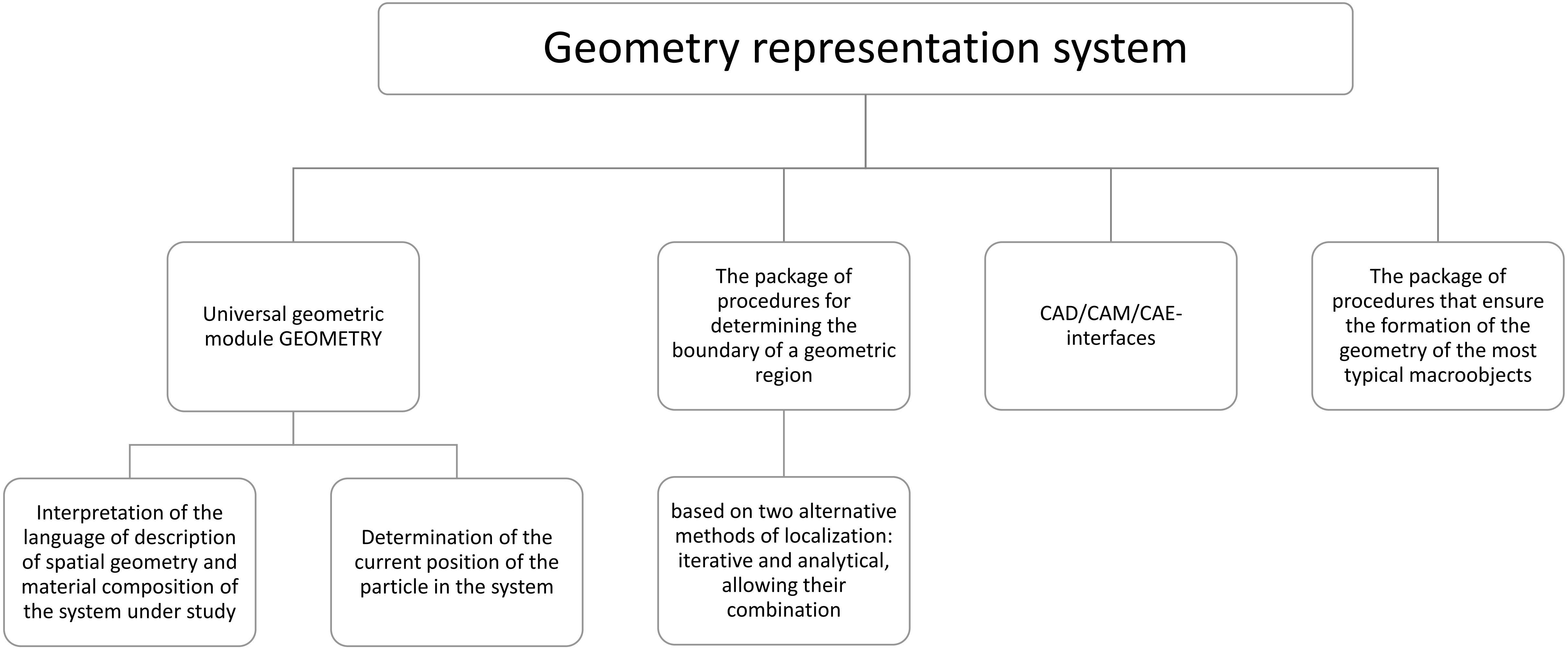
Software environment of the complex

- Procedures for initialization the source of primary radiation
- Procedures for initialization and parsing input data
- Procedures for initialization, parsing and visualization geometric data
- Procedures for writing and storing tree parameters for the paths in the modeling process (dynamically allocatable stack)
- Procedures for collecting, statistical processing and visualization of calculation results
- Procedures for initialization and preparation of constants

Flowchart of the framework of the RTS&T-2017 code



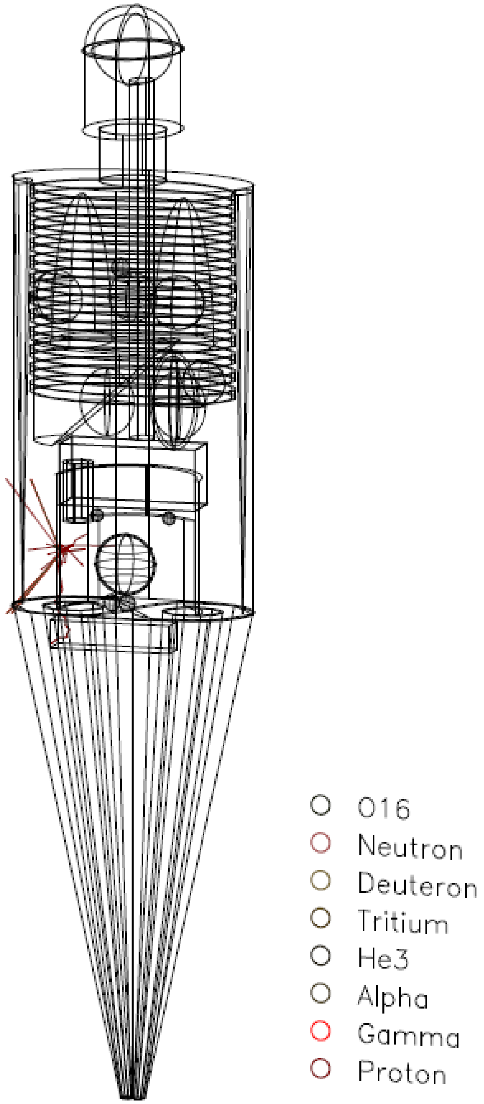
General information about RTS&T 2017



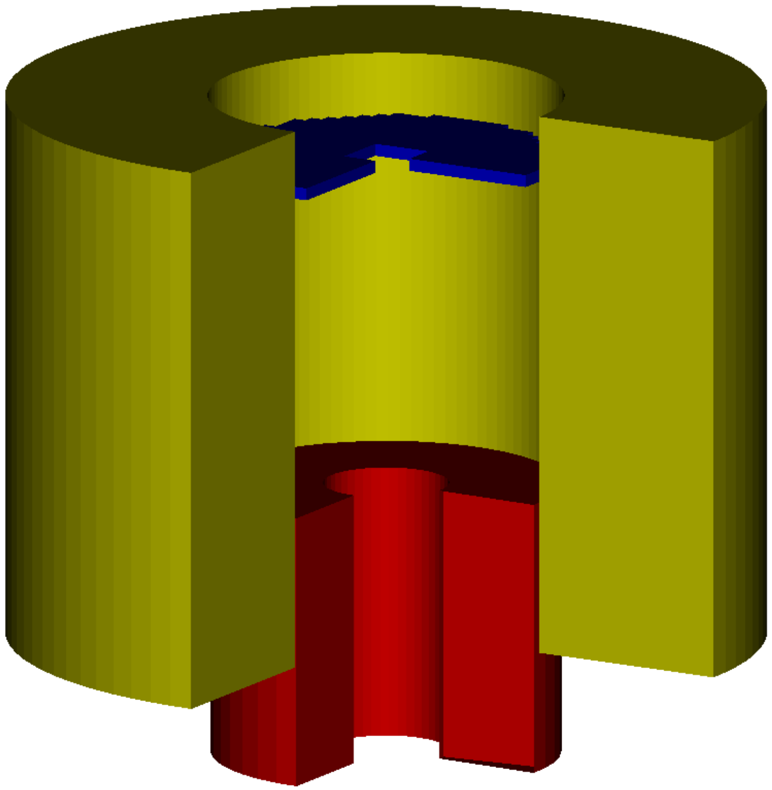
Example of visualization using GEOMETRY

For the visual presentation of the investigated object's geometry, transformation of the geometry input data to ASCII DXF format was applied. This format, designed by Autodesk, is a standard format for exchange by graphical information between AutoCAD and other applications.

Examples of visualization using GEOMETRY



3D-model of a mathematical phantom MIRD-2



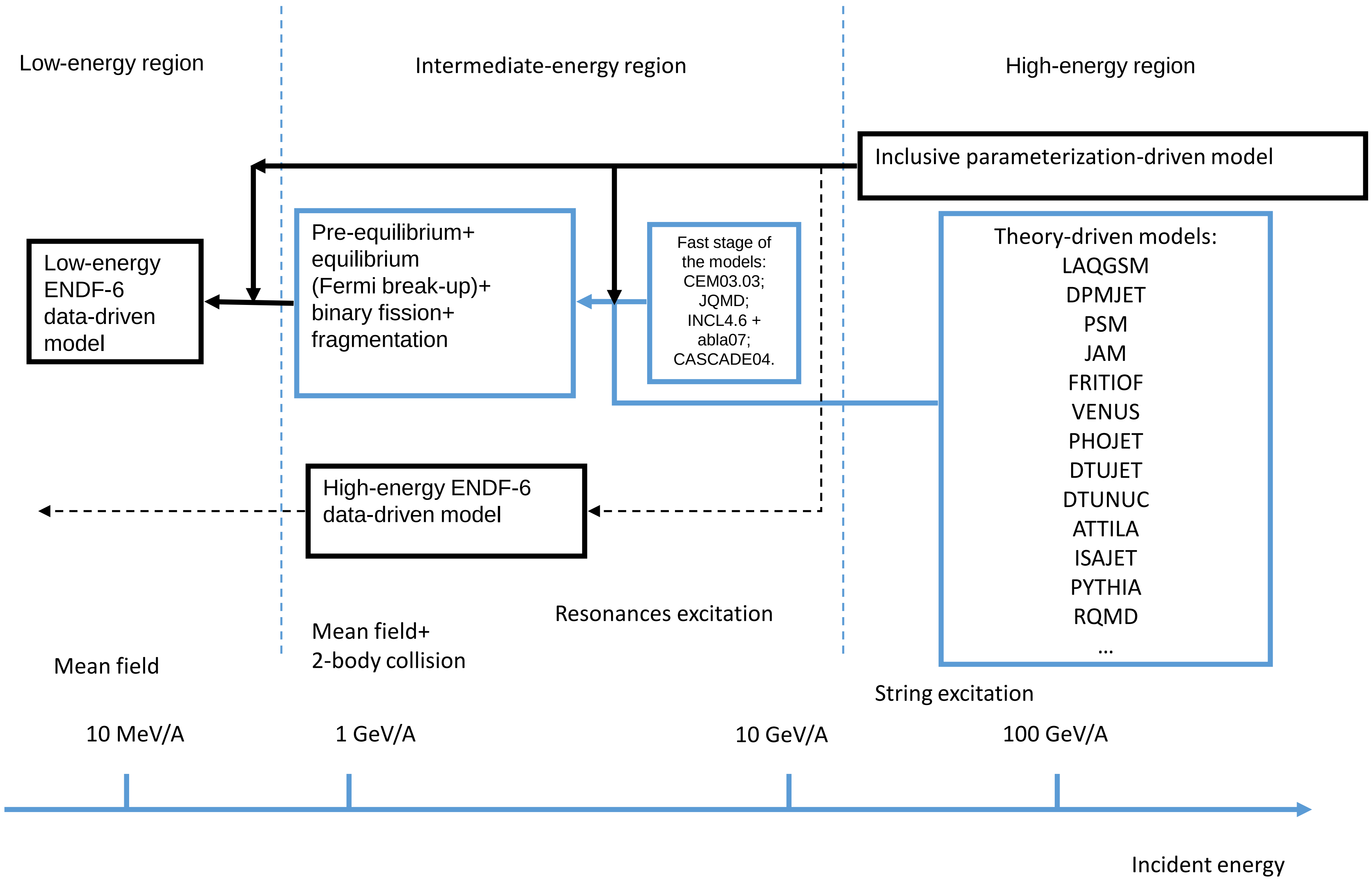
Solid-state 3D model of calorimeter E391a for KEK

Three groups classification of hadronic generators

RTS&T used classification:

1. Data-driven models (based on ENDF-6 format)
2. Parametrization-driven models (Macro models)
3. Theory-driven models (Micro models)

Hadron generators models in package RTS&T 2017



TDM - Theory-driven models

Basic theory-driven models

Gribnov-Redge model

- Modified Gribnov-Redge model (including taking into account the secondary rescattered slow partons on intranuclear nucleons by introducing amplification of the diagrams of multimeron exchange)

Dual Parton Models

- DPMJET
- PHOJET
- DTUJET
- DTUNUC
- IRIS
- VENUS

Classic string models

- FRITIOF
- FRITIOF (Dubna modification)
- ATTILA
- Parton String Model (PSM)

Models based on perturbative quantum chromodynamics

- ISAJET
- PYTHIA
- HERWIG
- HIJING
- Parton Cascade Model

Quantum Molecular Dynamics models

- QMD
- RQMD
- UrQMD
- JAM
- JQMD

PDM - Parameterization-Driven Model

There are 10 main groups that can describe all processes occurring during the interactions between high and intermediate energy range hadrons and nuclei.

$$\tau_0 \approx 10^{-23} - 10^{-22} s$$

1. h + A → h + A (el)
2. h + A → h + A* (qel)
3. h + A → h* + A* (diffr)
4. h + A → h* + A*(s)
5. h + A → hadrons (g)
6. h + A → A* + hadrons (abs)

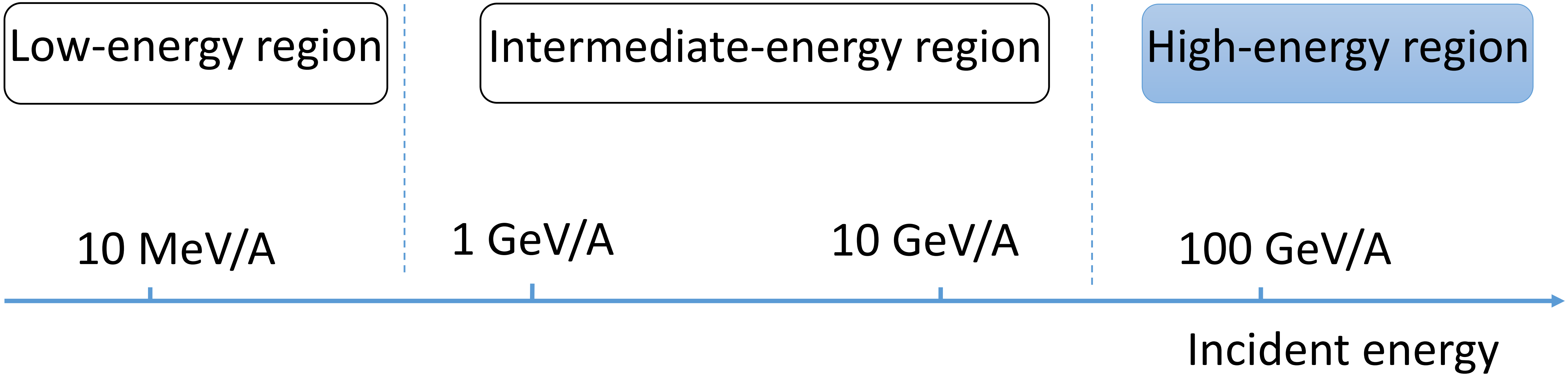
PDM - Parameterization-Driven Model

The group of processes aftercascade stage of reaction consists of:

$$\tau_0 \approx 10^{-18} - 10^{-16} s$$

7. Pre-equilibrium emission of secondary particles (gamma, nuclei and light slow clusters – d,t, He^3, α)
8. Evaporation of particles with A≤4 from medium-heavy nuclei or prompt Fermi break-up for nuclei with A<12
9. Binary fusion
10. Slow fragmentation

*) Degtyarev I.I., Novoskolsev F.N., Concepts of construction and results of the validation of the inclusive hadron generator of the RTS&T program complex in the range of intermediate and high energies based on modern experimental data, Herald of NRNU MEPhI, v. 2, №4, 2013, p. 461


Low-energy region
Intermediate-energy region
High-energy region
10 MeV/A
1 GeV/A
10 GeV/A
100 GeV/A
Incident energy

High-energy hadronic interactions

Main codes for hadron (nucleus)-nucleus inelastic collisions at E≥5 GeV in the package RTS&T 2017:

- PSM (Parton String Model)*
- LAQGSM (Los-Alamos Quark-Gluon String Model)**
- DPMJET-III (Dual Parton Model)***
- JAM (Jet AA Microscopic Transport Code)****
- Modified FRITIOF 7.02***** (The FRITIOF is a Monte Carlo code that implements the Lund string dynamics model for hadron-hadron, hadron-nucleus and nucleus-nucleus collisions).

  More than 20 decay channels of non-stable particle are available in current code version. The residual nucleus yields due to hA-, γA- and AA- interactions are available too.

*) N. Amelin, Preprint CERN/IT/99/6

**) K.K. Gudima, S.G. Mashnik and A.J. Sierk, Report LA-UR-01-6804, Los Alamos, 2001

***) S. Roesler, R. Engel, and J. Ranft. 2015. Springer. The Monte Carlo event generator DPMJET-III, in Proc. Monte Carlo 2000 Conference, Lisbon, Portugal, Oct. 2000,

****) Y. Nara, N. Otuka, A. Ohnishi, K. Niita, S. Chiba, Phys, Rev. C 61 (2000) 024901

*****) B. Anderson, et. al., Nucl., Phys 281B (1987) 289

High-energy hadronic interactions experiment

The probability of breakdown at various depths of the iron plate

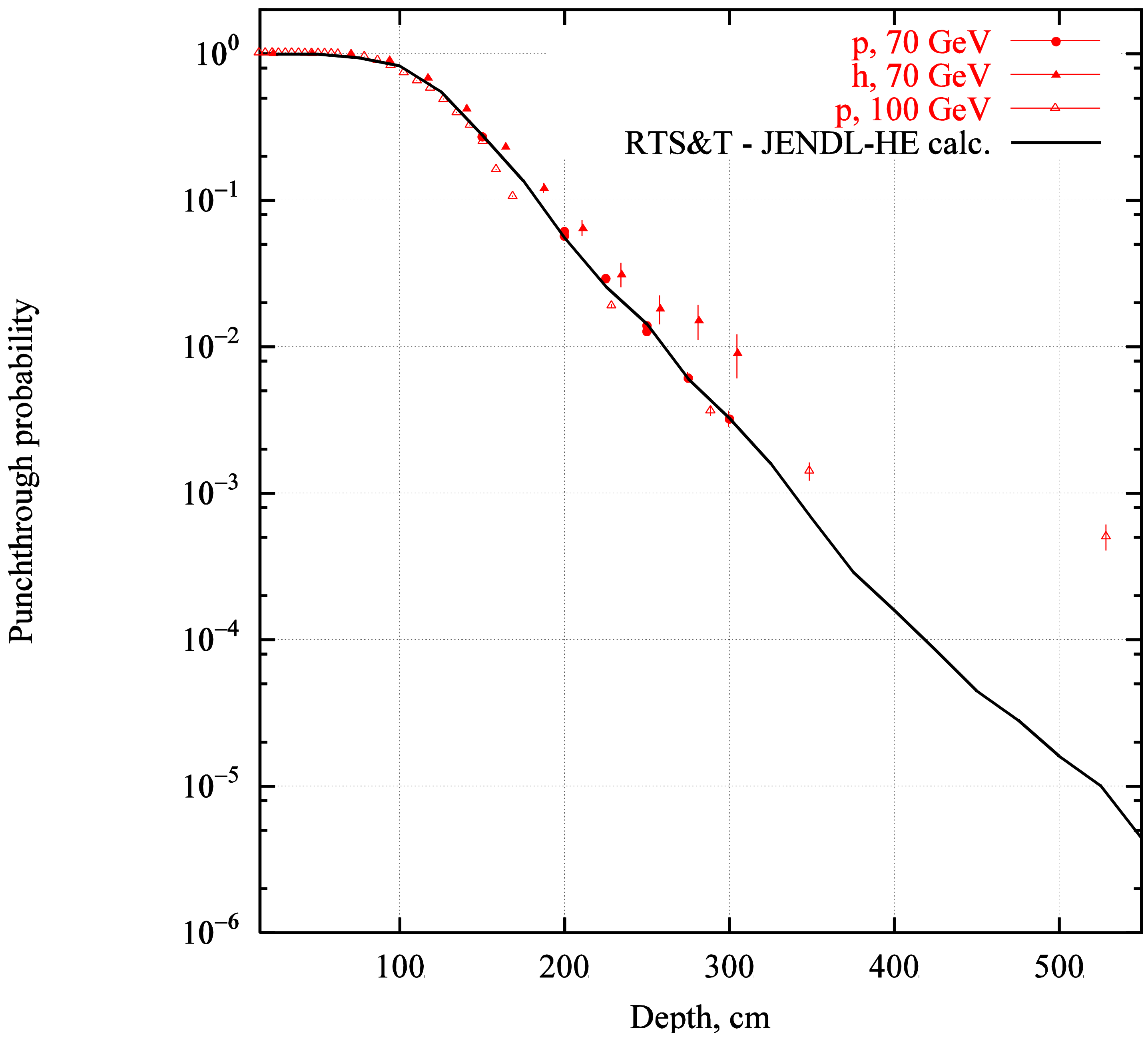
The probability of breakdown at various depths of the iron plate

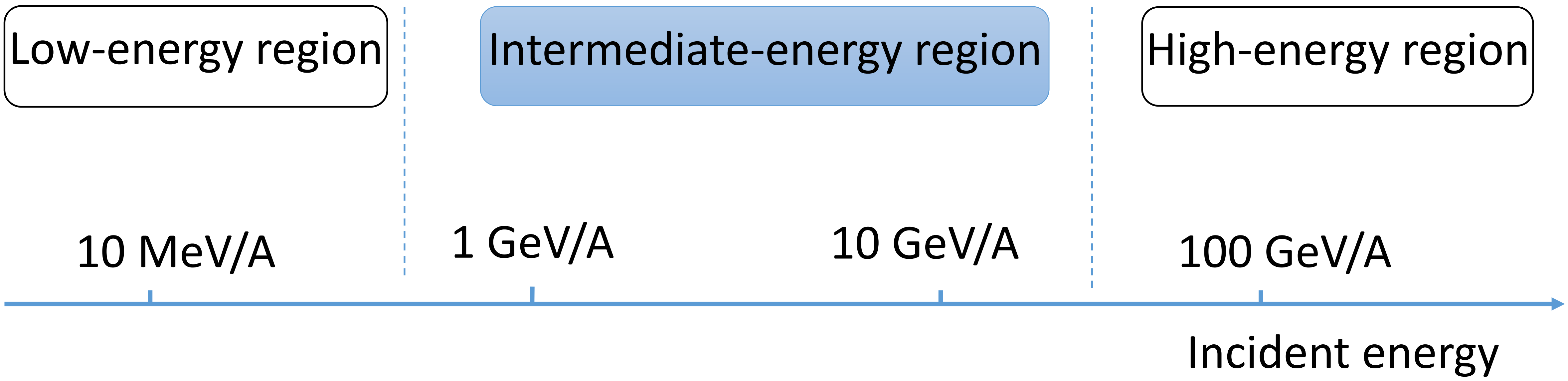
Calculation of the probability of the passage of a high-energy hadronic cascade through thick targets.

In Fig. (probability of breakdown) initiated by a proton beam with an energy of 70 GeV in an extended (L = 3 m) iron plate with experimental data obtained within the framework of the measurements of the project P-176* ("The last chance", IHEP). In the high-energy range, the macroscopic inclusive PDM generator (Parameterization-Driven Model) of the RTS&T complex was used to simulate hadronic interactions. In the region of intermediate energies, the simulation of the transfer of the nucleon component of the cascade was performed on the basis of direct use of the JENDL-HE library files

*) V.V. Ammosov et al., Study of the characteristics of penetrating radiation in steel upon the absorption of 70 GeV protons, Preprint IHEP 97-88, 1997.

Punchthrough probability as a function of cm of iron




Low-energy region
Intermediate-energy region
High-energy region
10 MeV/A
1 GeV/A
10 GeV/A
100 GeV/A
Incident energy

Intermediate-energy hadron interactions

In the RTS&T calculations, the hadron-induced nuclear reaction process in the energy region about 20 MeV to 5 GeV is assumed to be a three-step process of spallation (default configuration):

- Intra-nuclear cascade stage:
  - Dubna-version of intra-nuclear cascade model;
  - the Lindenbaum–Sternheimer isobar model for single- and double-pion production in nucleon-nucleon collisions and single-pion production in pion-nucleon collisions;
- Pre-equilibrium decay of residual nucleus:
  - The exciton model;
- The compound nucleus decay process:
  - Evaporation
  - High-energy fission competition.

Intermediate-energy hadron interactions

Additional generators for simulation of intermediate-energy hadron interactions in the latest version of the RTS&T code:

- The CEM03.03 (Cascade-Exciton Model);
- JQMD (JAERI Quantum Molecular Dynamics);
- INCL4.6 + abla07 (Liege Intra-nuclear Cascade model + GSI de-excitation code);
- CASCADE04 (Intra-nuclear Cascade + Pre-equilibrium + Equilibrium/Fission).

Intermediate-energy hadronic interactions experiment

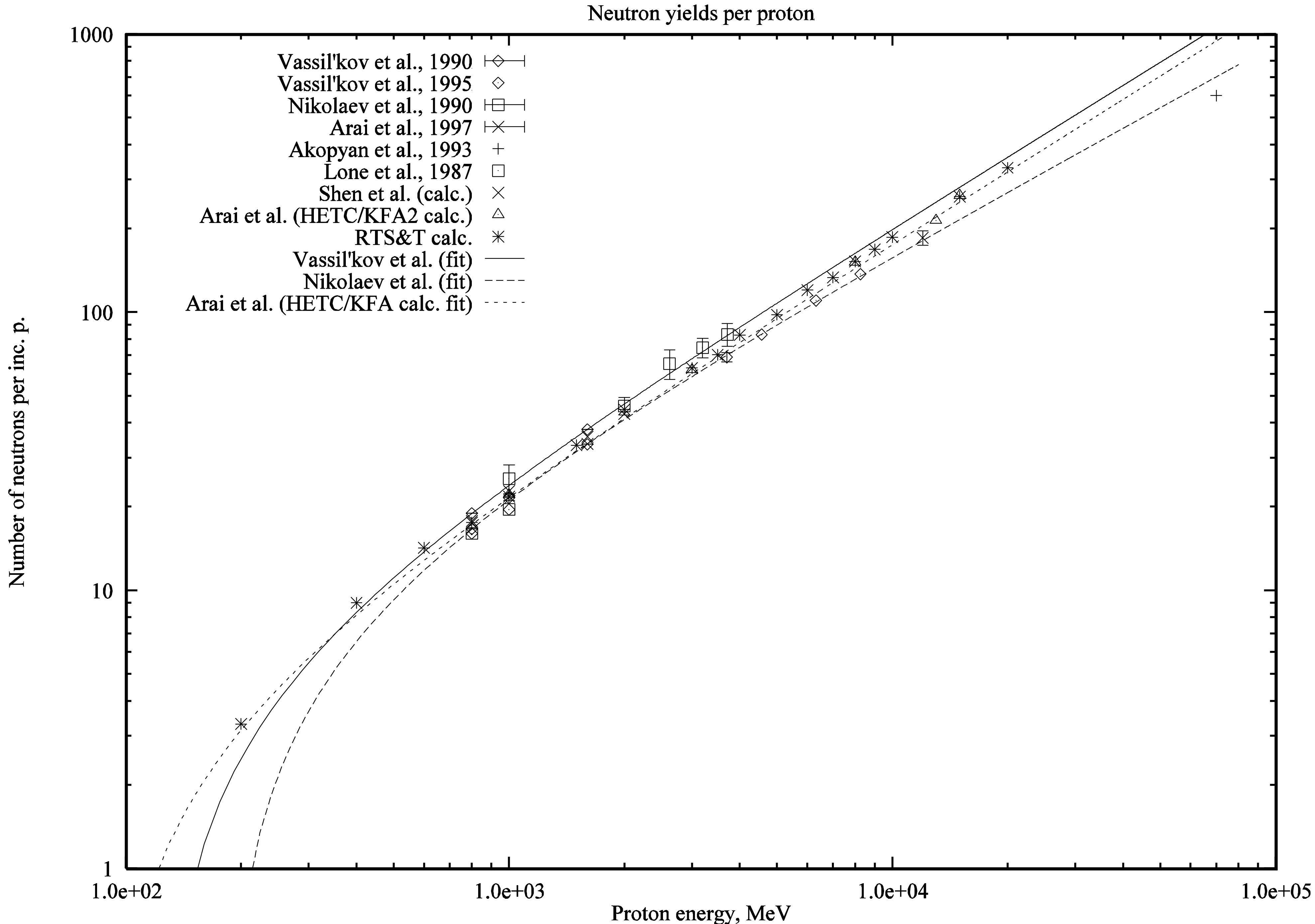
Integral yield of neutrons from the targets of total absorption

Integral yield of neutrons from the targets of total absorption

In Fig. The energy dependence of the integrated yield of neutrons from a lead cylindrical target (D = 20 cm, L = 60 cm) irradiated by a narrow beam of intermediate-energy protons is presented. The results of numerical simulation are compared with the compilation of experimental data*,**. When calculating the transfer of energy nucleons below 150 MeV, the estimated data files of the library LA150 were used. Fig. demonstrates the comparison of the results of modeling the integrated neutron yields within the framework of the RTS&T code with the JENDL-HE library with the experimental data obtained at the Berlin Neutron Ball (BNB) facility.

*)R.G. Vassil'kov et al., In ICANS-XI, number KEK-90-25, p. 340, 1990. Atomn. Energia 70 (1995) 257 (in Russian)

**)M.S. Lone et al., Nucl. Instr. Meth. A, 256:135, 1987



Neutron yields per proton
Vassil'kov et al., 1990
Vassil'kov et al., 1995
Nikolaev et al., 1990
Arai et al., 1997
Akopyan et al., 1993
Lone et al., 1987
Shen et al. (calc.)
Arai et al. (HETC/KFA2 calc.)
RTS&T calc.
Vassil'kov et al. (fit)
Nikolaev et al. (fit)
Arai et al. (HETC/KFA calc. fit)
1000
100
10
1
1.0e+02
1.0e+03
1.0e+04
1.0e+05
Number of neutrons per inc. p.
Proton energy, MeV

Intermediate-energy hadronic interactions experiment

The energy release of protons in cylindrical targets of total absorption

The XXII International Scientific Conference of Young Scientists
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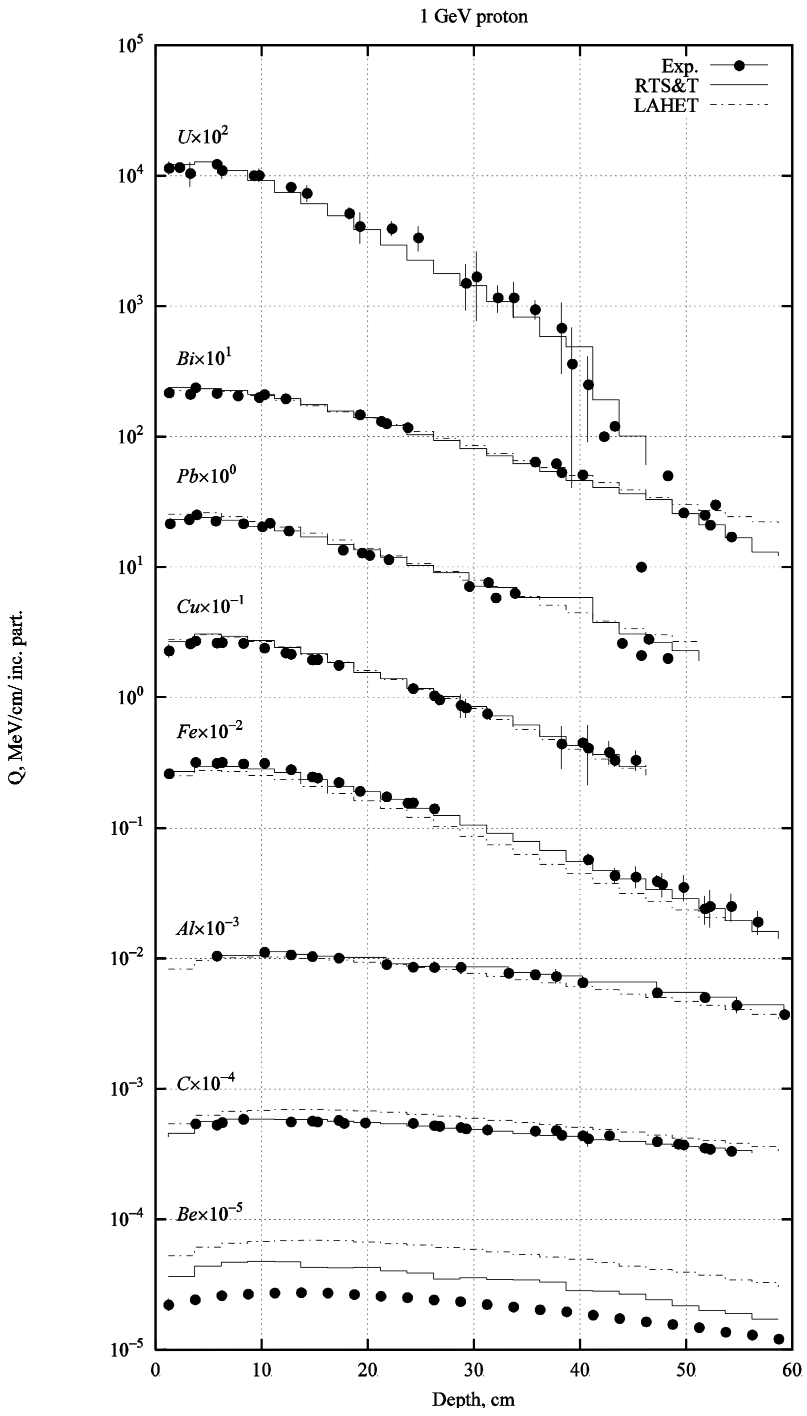
The energy release of protons in cylindrical targets of total absorption

The method of calorimetric measurements of heat release is described in detail in Ref. In Fig. (d = 20 cm, L = 60 cm) from Be, C, Al, Fe, Cu, W, Pb, Bi, U irradiated by a narrow monoenergetic proton beam (E 0) = 1 GeV). Results of numerical modeling within the framework of the RTS&T complex are compared with experimental data and calculation results according to the program LAHET 2.8 *, **.

*) C. Beard and V.I. Belyakov-Bodin, Comparison of Energy Deposition Calculation by the LAHET Code System with Experimental Results, Nucl. Sci. Eng., № 87-96, 1995, p. 119.

**) V.I. Belyakov-Bodin et al., Calorimetric Measurements of Heat Deposition in Targets from Lead and Bismuth Bombarded by Medium-Energy Protons, Nucl. Instr. Meth. A, №373, 1996, p. 3



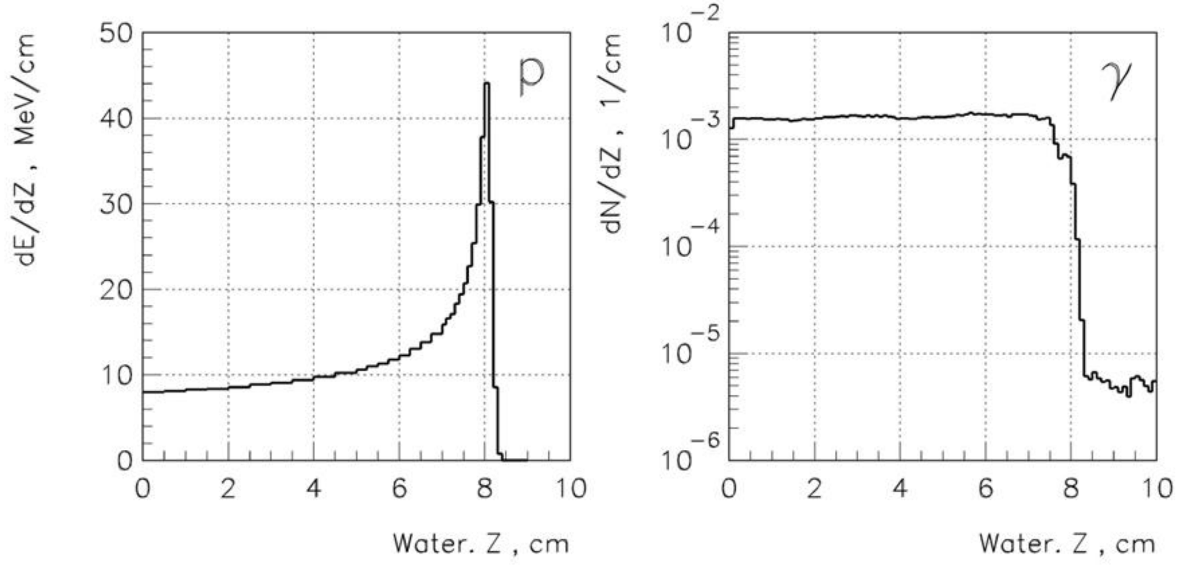
1 GeV proton
Exp.
RTS&T
LAHET
U×10^2
Bi×10^1
Pb×10^0
Cu×10^−1
Fe×10^−2
Al×10^−3
C×10^−4
Be×10^−5
Q, MeV/cm/ inc. part.
Depth, cm

Intermediate-energy hadronic interactions experiment

Hadron therapy application

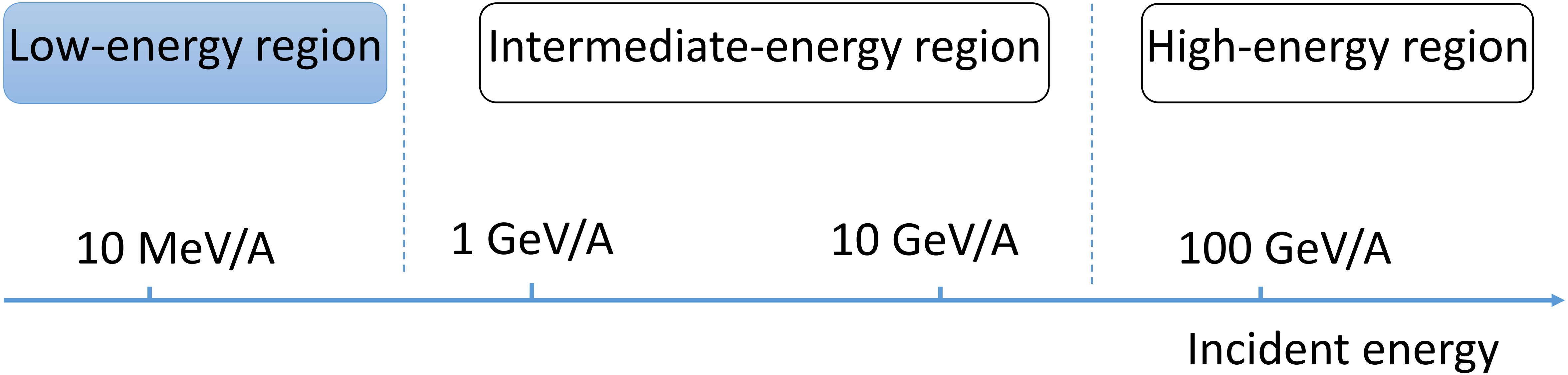
Hadron therapy application

RTS&T code was used for the verification of the method for real-time monitoring of the Bragg peak position in a water phantom during scanned proton pencil-beam irradiation. The result were presented in these works*,**.



*) A.A. Pryanichnikov et al., Numerical simulation of real-time Bragg peak position detection based on the registration of prompt gamma rays in the orthogonal direction for application in hadronic therapy, Problems of Atomic Science and Technology. Series: Nuclear and Reactor Constants, 2018, is. 1, 1:12.

**) V.E. Balakin et al., Theoretical research and development of a clinical setup prototype for on-line monitoring of the Bragg peak position for proton therapt complex “Prometheus”, Physics of Particles and Nuclei Letters №7, 2018.


Low-energy region
Intermediate-energy region
High-energy region
10 MeV/A
1 GeV/A
10 GeV/A
100 GeV/A
Incident energy

Low-energy hadronic interactions

Main features of RTS&T 2017 in low energy range:

- The continuous-energy nuclear and atomic evaluated data files to simulate of radiation transport and discrete interactions of the particles in the energy range from thermal energy up to 20/150/3000 MeV;
- The ENDF-data driven model of the RTS&T code has direct access to evaluated data;
- All data types provided by ENDF-6* format;
- The universal data reading and preparation procedures allows to use of various data library written in the ENDF-6 format (ENDF/B, JENDL, JENDL-HE, FENDL, CENDL, JEF, BROND, LA150, ENDF-HE/VI, IAEA Photonuclear Data Library etc.).**

*) ENDF-102 Data Formats and procedures for the evaluated data file ENDF-6, BNL-NCS 44945, July 1990.

**)A.A. Pryanichnikov et al., Verification of the world evaluated nuclear data libraries on the basis of integral experiments using the RTS&T code system, Problems of Atomic Science and Technology. Series: Nuclear and Reactor Constants, 2018, is. 1, 1:13.

Low-energy hadronic interactions

Main features of RTS&T 2017 in low energy range:

- Minimization of the amount of data using the ENDF-6 interpolation laws and storage organization using the dynamically allocated tree of object;
- All types of reactions provided by ENDF-6 format are taken in to account for the particle transport and discrete interactions modeling: elastic scattering and reactions with production of one neutron in the exit channel, absorption with production of other type particles (with division on excited states of the residual nucleus), the fission with separate yields of prompt and delayed neutrons and residual nucleus simulation by MF=8 data, etc. The energies and angles of emitted particles are simulated according to the distributions from MF=4, 5, 6, 12, 13, 14 and 15 files.

ENDF data pre-processing

linearization	restoration of the resolved resonances	temperature dependent Doppler broadening of the cross sections	checking and correcting of angular distributions and Legendre coefficients
LINEAR	RECENT	SIGMA1	LEGEND

All codes are rewritten in ANSI standard FORTRAN-90.

*)D.E. Gullen, IAEE-NDS-39”, Rev. 9, 1996

Low-energy hadronic interactions experiment

Integral experiments on the output of secondary neutrons from the surfaces of spherical assemblies

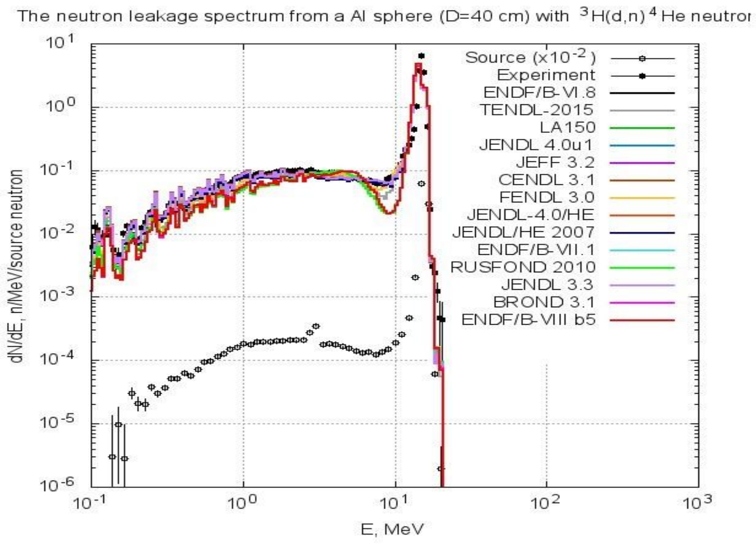
Integral experiments on the output of secondary neutrons from the surfaces of spherical assemblies* from the SINBAD collection.

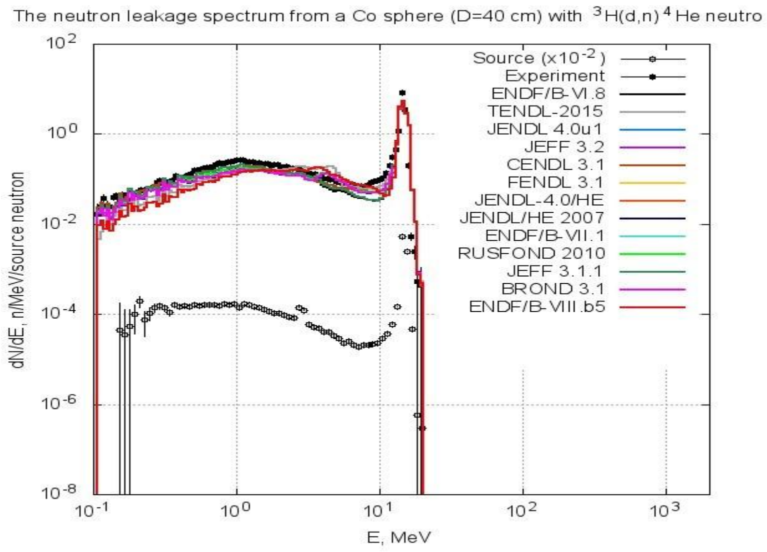
A point isotropic source of neutrons in the spectrum of the $^{3}H(d,n)^{4}He$ -reaction was located at the center of spherical mock-ups (D = 40, 60 cm). The detailed results of this experiment can be found in this work**.

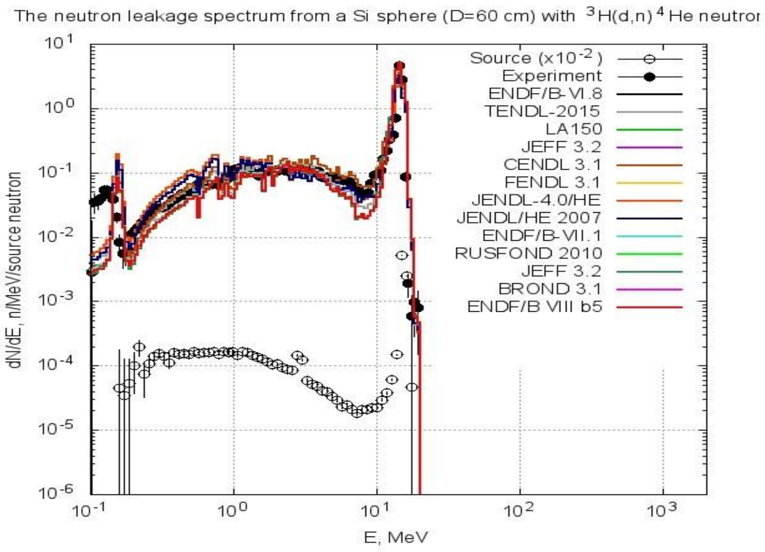
*) Ch. Ichihara et al., Leakage Neutron Spectra from Various Sphere Piles with 14 MeV Neutrons, JAERI-M 94-014, p. 63, 1994.

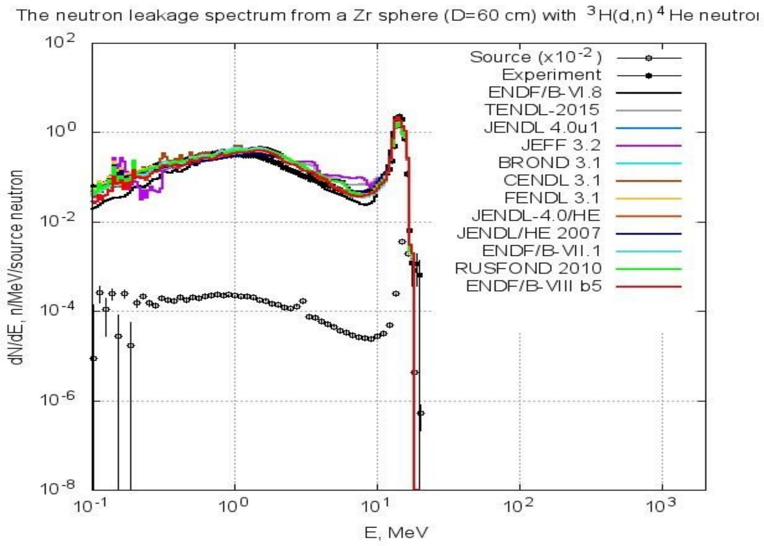
**)A.A. Pryanichnikov et al., Verification of the world evaluated nuclear data libraries on the basis of integral experiments using the RTS&T code system, Problems of Atomic Science and Technology. Series: Nuclear and Reactor Constants, 2018, is. 1, 1:13.

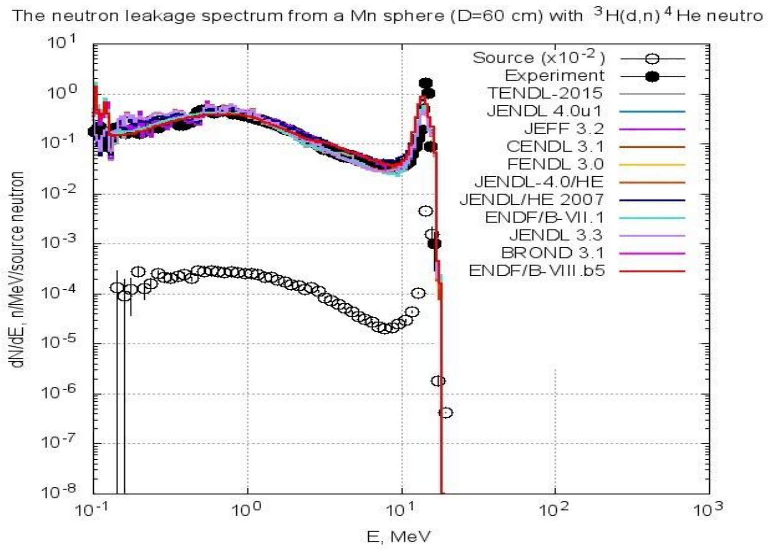
Neutron leakage spectra from the surface of spherical assemblies

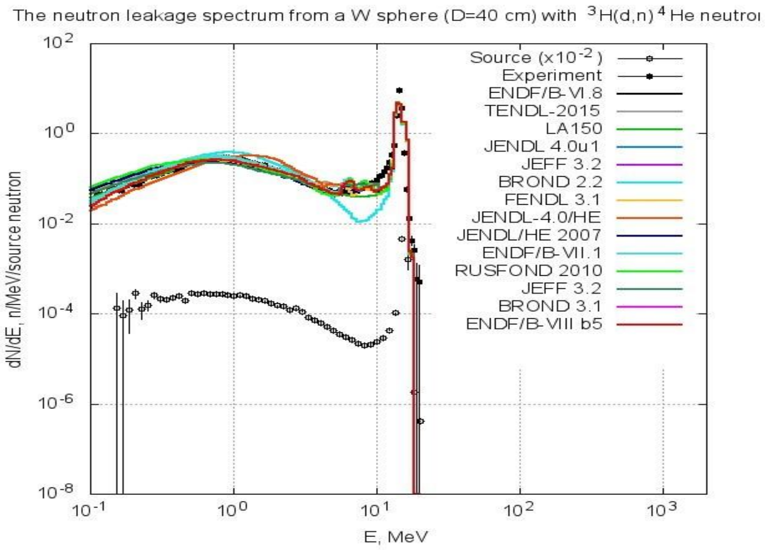




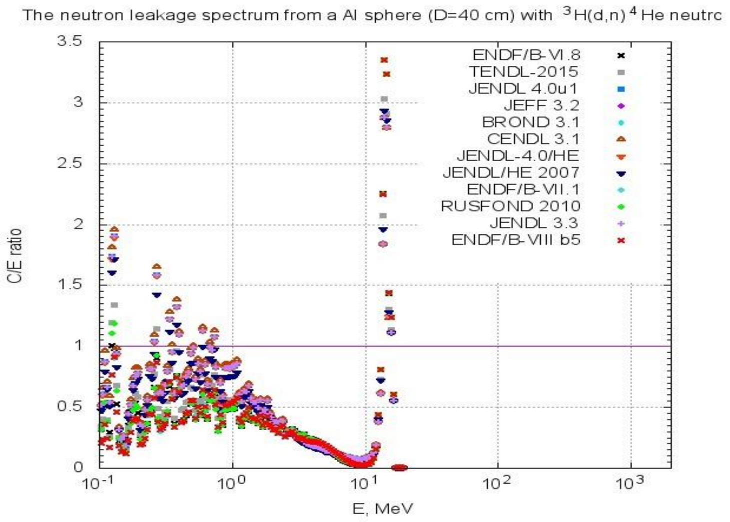


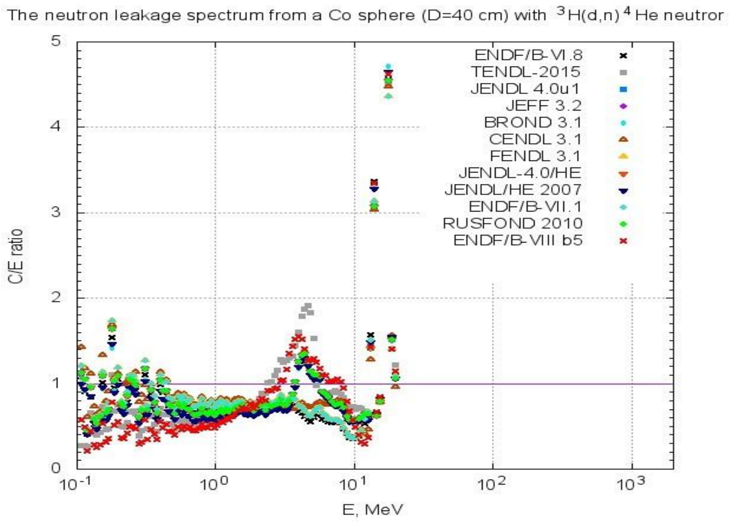


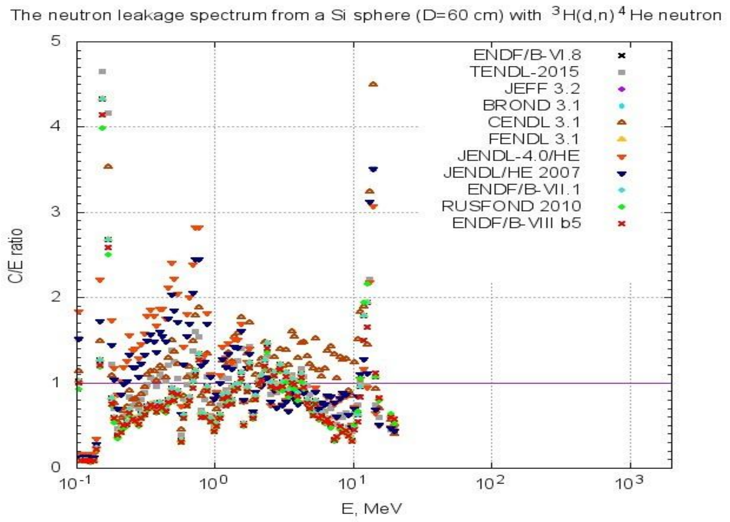


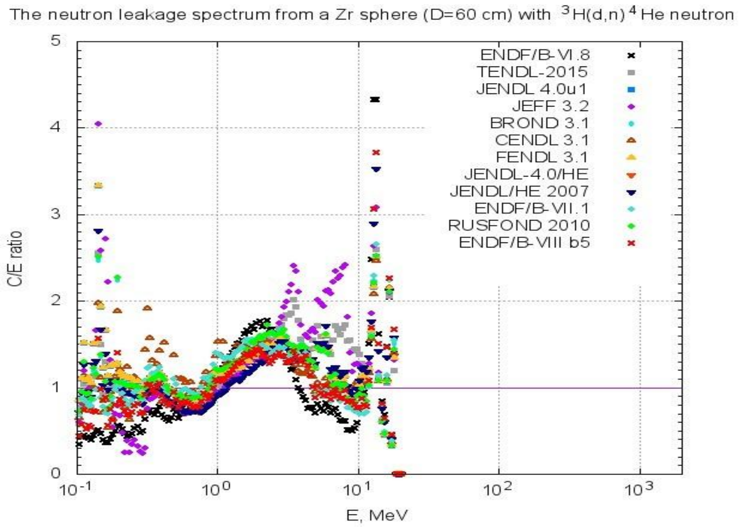


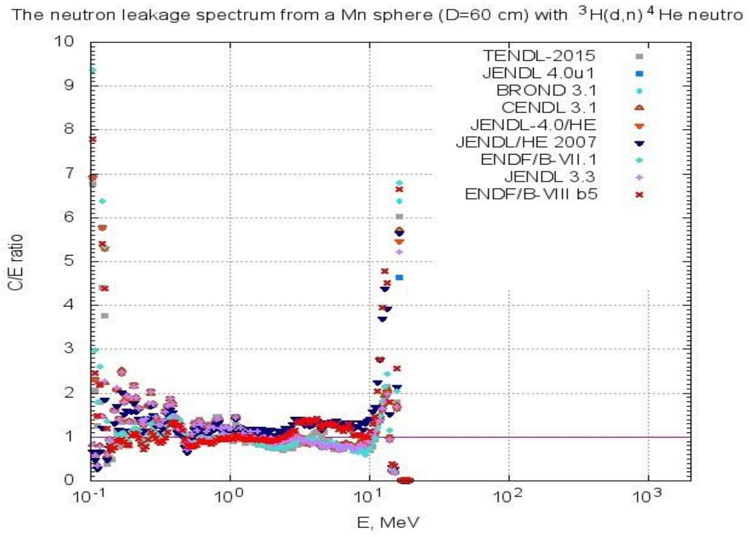
C/E ratio of neutron leakage spectra from the surface of spherical assemblies

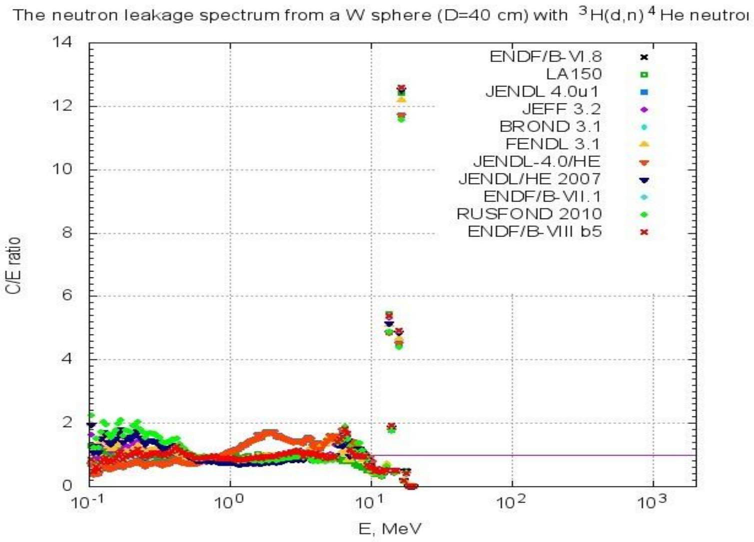












Resulting value χ^2/DoF table

The Library of Evaluated Nuclear Data	Material of assembly					
	Al	**Si**	**Mn**	**Co**	**Zr**	**W**
BROND 3.1	34.1072311	0.1409222	0.0376164	0.1777702	0.0196693	0.2955392
CENDL 3.1	34.5067024	0.0848230	0.0262865	0.1747213	0.0197966	-
ENDF/B VI.8	34.3722305	0.1284287	-	0.1778001	0.0375658	0.2959574
ENDF/B VII.1	34.1160583	0.1284287	0.0432632	0.1752771	0.0246908	0.2955631
ENDF/B VIII beta5	34.1074867	0.1209213	0.0376164	0.1742702	0.0193236	0.2955359
FENDL 3.1	-	0.1258727	0.0353412	0.1752771	0.0189309	0.2939239
JEFF 3.2	34.3725700	0.1421800	0.0353412	0.1752814	0.0251943	0.2917682
JENDL 4.0	34.7610397	0.0738185	0.0403688	0.1750326	0.0189309	0.3003758
JENDL 4.0-HE	34.5016556	0.0738185	0.0403688	0.1750326	0.0227736	0.3003764
JENDL-HE-2007	34.4260254	0.0806130	0.0251958	0.1775477	0.0227728	0.2930388
RUSFOND 2010	34.1160583	0.1421800	-	0.1750326	0.0196335	0.3059505
TENDL 2015	34.6310806	0.0660777	0.0335942	0.1788945	0.0204340	-

Summary

Methods for describing the discrete nuclear interactions of hadrons in the range of low, intermediate and high energies, the geometry representation system of the code system RTS&T were presented in this report. The results of a selective comparison of the results of numerical simulation with correct experimental data were provided too.

References

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