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A REVIEW OF MODELS AND CODES FOR NEUTRON SOURCE(SPALLATION)CALCULATION FOR ADS APPLICATION

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ABSTRACT

This paper reviews the physics of the spallation process induced by high energy protons. Given the high energy of the incident proton, in a first stage it interacts with the individual nucleons in initiating an intra-nuclear cascade which leads to the emission of secondary particles (neutrons, protons, mesons, etc.). In a secondary stage the nucleus is left in an excited state and can de-excite by evaporation and/or fission. Due to the high number of secondary neutrons produced (~30 n/p for proton energy of 1 GeV), this reaction can be used as a source of neutrons, for example for ADS systems. Since in ADS the source of neutrons is an external spallation source, this paper also reviews the main codes used in the ADS target design. As an example, the utilization of one of these codes (the LAHET code) for typical ADS target is given. The CRISP code in development for ADS application by IFUSP and CBPF will be illustrated with results for the neutron multiplicity for thin targets..

1. INTRODUCTION

The Accelerator Driven System (ADS), is an innovative reactor which is being developed as a dedicated burner in a Double Strata Fuel Cycle to incinerate nuclear waste [1].
The ADS consist of a sub-critical assembly driven by accelerator delivering a proton beam on a target to produce neutrons by a spallation reaction.
The spallation module constitutes the physical and functional interface between the accelerator and the sub-critical reactor. For this reason it is probably the most innovative component of the ADS. The target design is a key issue to investigate in designing ADS and its performances are characterized by the number of neutrons emitted for incident proton, the mean energy deposited in the target for neutron produced, the neutron spectrum and the spallation product distribution.
The physics of the spallation mechanism, the different models developed to describe this mechanism and the codes in which they are implemented will be reviewed in this work. Some results using the LAHET and CRISP codes system will be illustrated.

2 THE SPALLATION REACTION PHYSICS

Spallation[2,3,4,5,6,7,8] is a nuclear reaction in which a relativistic light particle like a proton or a neutron hits a heavy nucleus. The energy of the incoming particle usually varies between a few hundred of MeV and a few GeV per nucleon. In a first approximation this interaction process can be grossly divided in two steps.

<u>In the first stage</u>, usually known as intra-nuclear cascade, the incoming nucleon makes a few, mainly incoherent scattering with nucleons of the target, depositing in this way some fraction of its energy.
As a matter of fact the reduced wavelength ($\lambdabar$) of a few hundred of MeV incoming nucleon is about 10^{-14} cm, which is smaller than the distance between nucleons, usually about 1 fermi (10^{-13} cm). In this way the incoming nucleon sees the substructure of the nucleus, i. e. a bundle of nucleons. This fast stage (typical duration of the intra nuclear cascade: 10^{-22} s) of

nucleon-nucleon scattering interaction leads to the ejection of some of the nucleons and to the excitation of the residual nucleus which will cool itself afterwards (in the second stage).
When the intra nuclear cascade is finished and the last nucleon has been ejected, the nucleus is being left in an excited state.
The second stage is supposed starting after the incoming proton has left the target and involves the propagation and the dissipation of the energy gained by the nucleus. Typical duration of the de-excitation process is 10^{-16} seconds.
The de-excitation of the residual nucleus can proceed in two main ways: evaporation and fission.
The evaporation is the dedicated de-excitation channel for non –fissile or hardly fissile nuclei which have been excited above the energy required for the separation of the neutron. In this process the excited nucleus emits nucleons or light nuclei such as D, T, He, α, Li, Be.
The second important de-excitation mode is fission. In the fission process the nucleus is ultimately "cut" into two fragments of different masses. This process of high energy fission generally leads to two more symmetric fission fragments with respect to a thermal fission process.
During the de-excitation emission of photons is also possible. The nucleus emits particles until its energy of excitation goes below the binding energy of the last nucleon. At this state about 8 MeV are remaining and will be evacuated out of the nucleus by γ radiation.
The de-excitation process does not end with the ending of the γ emission. In fact the nucleus resulting after γ decay is often a radio-isotope which will decay until the corresponding stable nucleus is reached.

During the de-excitation process of a spallation reaction, a certain number of neutrons is emitted. It can be interesting to quantify this number in view of possible use of the spallation reaction as source of neutrons. This number is strictly dependent on the target composition and size as well as on the energy and type of the incident particle

2. 1 Review of the reaction models

In the previous section a general idea of the spallation mechanism has been given.
The interaction process between a fast incoming particle and a nucleus has been grossly divided into two different steps: the intra-nuclear cascade and the de-excitation process. Each of these steps is generally described by a physical model (which corresponds to a physical description of the phenomena) which is subsequently simulated by using the Monte Carlo method.
Presently two major types of intra nuclear cascade **(INC)** models exist. They correspond to two different approach of the nucleus.
The first approach was developed in the sixties by Bertini and it is incorporated into MCNPX through the LAHET implementation.
While in all the previous models the nucleon density within the nucleus was supposed to be constant, Bertini represents the nuclear density by three density steps describing the nucleus through three concentric spherical zones characterized by a given nuclear density and a given nuclear potential. The interaction process between the incoming particles and the nucleons is described in terms of the particle mean free path $\lambda=(\rho\sigma)^{-1}$ in the medium. After each path the particle scatters on a nucleon with which it exchange energy. Without entering in details we can just note that the stopping criterium of the Bertini cascade is the Bertini cut-off energy.

The most recent version of the Bertini-like cascade has been developed by Yariv and Frankel and has led to the ISABEL model (the nuclear density is represented in 16 steps) available in MCNPX.
Another INC model, CEM (Cascade Evaporation Model), is available in the MCNPX code. CEM is a model developed in Dubna, Russia.
The second model was developed in the eighties by Cugnon [8]**.** The Cugnon model describes the nucleus as a sphere over which the nuclear density is constant (recently a radial dependence of the density has been considered). The nucleus is not considered a continuous medium as in the Bertini model but as a bundle of individual nucleons moving in a given potential. When an incoming nucleon enters inside the nucleus it is then regarded as a part of the nucleus and is therefore described just as the other nucleons of the nucleus. A consequence of such a description of the nucleus is that the criteria for interaction between the nucleons are now the distance between them. Scattering happens when two nucleons are closer to each other than a minimal distance d_{min}, depending on the total interaction cross section. There can be elastic or inelastic scattering. The stopping criteria for the Cugnon cascade is the Cugnon cut off time which is the time at which the intra nuclear cascade is stopped and gives way to evaporation.
To describe the second step of the spallation reaction are available different de-excitation models in dependence of the de-excitation channels. The two major de-excitation channels are evaporation and fission but there are models describing also de-excitation through γ emission and nuclear decay

2. 2 Simulation codes

Two widely used transport codes used to simulate the spallation reaction are:
The LCS (LAHET Code System) [9] code, developed at Los Alamos National Laboratory. The LAHET Code System was developed at Los Alamos National Laboratory. LAHET (Los Alamos High Energy Transport Code) is a Monte Carlo code for treating the transport and interactions of nucleons, pions, muons, light ions and antinucleons in complex geometry. LAHET includes both the Bertini and the ISABEL intranuclear cascade model as user options. An evaporation model for the breack-up of light nuclei is also included. An optional multistage pre-equilibrium model has been implemented as an intermediate stage between the intranuclear cascade and the evaporation phase of a nuclear reaction. Alternative level density parameterization are also included.
The FLUKA (FLUctuating KAscade simulation program) [10] code, developed at CERN.is a Monte Carlo code able to simulate transport and interaction of electromagnetic and hadronic particles in any target material over a wide range of energies. FLUKA use the PEANUT (Pre-Equilibrium Approach to Nuclear Thermalization) model to describe inelastic nuclear interaction. This model consists of intra-nuclear cascade (INC), pre-equilibrium, evaporation and de-excitation. The current version of the code (FLUKA-EA-MC) can simulate neutron interaction and transport down to thermal energies (multi group below 20 MeV) and hadron-hadron and hadrons-nucleus interactions up to 100 TeV. The validity of the physical models implemented in FLUKA has been benchmarked against a variety of experimental data over a wide energy range, from accelerator data to cosmic rays data. The FLUKA code has been used for spallation reaction simulation in the Energy Amplifier (EA) project.
The MCNPX [11] code is another option based on the fully integration of the LAHET code in the MCNP [12] code environment, it only needs of one input file for both codes, avoiding the transfer of large data files.

Recently a Brazilian research group (IFUSP and CBPF) developed the MCMC/MCEF (MultiCollisional Monte Carlo plus Monte Carlo for Evaporation-Fission calculation) model to study nuclear reaction such as spallation. The MCMC and the MCEF model utilize the Monte Carlo approach to describe the intra-nuclear cascade and the evaporation/fission processes respectively. Their coupling originates the CRISP (Colaboração RIo-São Paulo) package [13]. The code takes into account the possibility of neutron, proton and alpha particle evaporation and gives information about neutron and proton multiplicity, angular distribution and energy spectra.

. The CRISP results where compared with results obtained with the LAHET code using both the Bertini and the ISABEL model and with experimental data. A very good accordance with experimental data was registered.[16,17]

3. RESULTS

As an illustration of a typical windowless ADS target system, as that proposed in the XADS (eXperimental ADS) or in MYRRHA projects [14, 15], the neutron multiplicity (n/p) and the total energy deposited in the target per incident proton was calculated by LAHET for the configuration illustrated in figure 1. The results are illustrated in table 1.

Results of the CRISP for thin target compared with experimental results and the results from others codes are illustrated in table 2. Presently, the CRISP code is being incorporated into MCNPX.

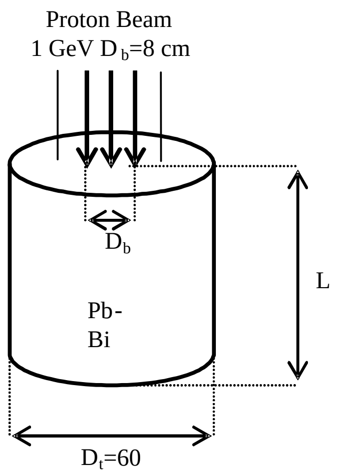

Figure 1: Typical Lead Bismuth Windowless Target system

L(cm)	n/p	MeV/p
10	9.08	232.518
20	16.087	399.341
30	20.859	501.573
40	23.480	557.927
50	24.954	591.848
60	25.769	615.576
70	26.028	617.512
80	26.238	619.738
90	26.322	620.455
100	26.417	621.317

Table 1: Neutron Multiplicity (n/p) and Energy deposited in the Target per incident proton calculated by LAHET.

Energy	**Expt[*].**	**CRISP**	INCL4 KHSv3p	TIERCE Cugnon	LAHET Bertini	LAHET ISABEL	LAHET Bertini-preq
			Pb T_{lab} = 800 MeV				
0 - 2 MeV		**4.24**	3.3	4.9	5.61	5.13	5.37
2 - 20 MeV	**6.5**	**6.36**	6.8	6.9	8.63	6.63	7.12
20 MeV - E_{max}	**1.9**	**2.06**	2.5	2.2	1.75	1.92	2.13
Total		**12.7**	12.5	14.0	16.0	13.7	14.04
			Pb T_{lab} = 1200 MeV				
0 - 2 MeV		**4.65**	3.4	5.8	6.35	--	6.02
2 - 20 MeV	**8.3**	**6.98**	8.1	8.9	11.44	--	9.86
20 MeV - E_{max}	**2.7**	**2.47**	3.1	2.8	2.45	--	2.83
Total		**14.1**	14.7	17.4	20.2	--	18.7

Table 2: Neutron multiplicities in proton-induced reaction on Pb nuclei

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