

# THE PHENOMENOLOGY AND EXPERIMENT OF SPALLATION PROCESSES\*

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Spallation reactions are of large interest for application driven aspects and also highly relevant for basic research in fundamental physics. The relevance of and need for high quality nuclear data is discussed in the context of validation and development of computer models for spallation reactions. Limits and constraints of most recent intra-nuclear-cascade/evaporation models are pointed out and an emphasis is laid on the benchmark of spallation models carried out under the auspices of the IAEA.

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## 1. Introduction

The definition of the term “spallation reaction” found in Encyclopedia Britannica reads as follows: *“high-energy nuclear reaction in which a target nucleus struck by an incident (bombarding) particle of energy greater than about 50 million electron volts (MeV) ejects numerous lighter particles and becomes a product nucleus correspondingly lighter than the original nucleus. The light ejected particles may be neutrons, protons, or various composite particles equivalent”*. This definition has to be specified in the context of accelerator driven systems or high intense neutron sources. Here, spallation is the disintegration of a nucleus by means of high energetic proton induced reactions. In this nonelastic nuclear interaction, typically approximately 20 neutrons are created per incident GeV proton. The interest for spallation reactions in applications comprises aspects of transmutation of nuclear waste, space technologies, production of isotopes, future tritium production units, astrophysics, biology and medicine, spallation-neutron sources, and

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radioactive-beam production. As for example, high intense powerful spallation neutron sources are currently planned or being built in Europe [1], the USA [2] and Japan [3]. For the design and engineering layout of such spallation sources, nuclear data and Monte Carlo model calculations play an utmost importance for maximization of the neutron flux, optimization of the target/moderator/reflector assembly in terms of geometry, and material, the estimation of expected radiation damage due to embrittlement, displacements per atom, the activation of structural materials and critical components, the expected energy deposition, and the anticipated transmutation rates.

The more fundamental physics driven aspect includes the study of decay modes of highly excited hot nuclear matter, the systematics on production cross sections for light isotopes (complex particles) and intermediate mass fragments in GeV  $pN$  reactions, and the understanding of the reaction mechanism and cluster formation (coalescence, cascade exciton model, successive elementary reactions). To this, it is of importance to decompose the evaporative and pre-equilibrium components and to systematically study comprehensive data sets on angular-, and energy distributions (over wide range of target nuclei). These observables provide the test grounds for model development and improvements and sensitive benchmarking.

In this contribution, we briefly mention a selection of state-of-the-art computer models and codes before advertising the IAEA benchmark of Spallation Models providing not only an expert platform on model codes for spallation reactions, but also a comprehensive data base for the spallation physics community.

## 2. Computer models for spallation reactions

The spallation reaction is generally described by microscopic models based on the assumption of two stages of the reaction, *i.e.*, the fast stage (time scales  $\approx 10^{-22}$  s) consisting in intranuclear cascade of nucleon–nucleon collisions — described by INC, BUU or QMD models, and the slow stage ( $\approx 10^{-18}$  to  $10^{-16}$  s) of the reaction in which the heavy target residua reach statistical equilibrium and evaporate particles ( $n, p, d, t, \alpha, \gamma$ ) — described by statistical models.

Typical codes currently being used for modelling these processes are the latest versions of the intranuclear cascade model INCL4.6 [4], the evaporation code ABLA07 [5], the statistical multifragmentation code SMM [6] and the GEMINI++ [7, 8] which describes the decay of excited nucleus by a series of binary decays. The primary goal of the comparison to the model calculations is to validate the implemented reaction mechanisms in the codes and test their capability of reproducing the experimental data. Here, it is of par-

ticular importance to measure double differential cross sections  $d^2\sigma/d\Omega dE$  rather than total cross sections only, thus imposing additional constraints for the theoretical models and understanding the complex reaction mechanism itself. Furthermore, the aim is to determine, whether the composite particles are predominantly emitted from an equilibrated nucleus, or during the fast intra-nuclear cascade phase via a coalescence mechanism.

In the following, the prerequisites and fundamental presumptions of intra-nuclear-cascade models (here focussed in particular on the model of Ref. [4], but essentially valid also for all typical INC models) are described:

- the hadron–nucleus interaction is a consequence of independent collisions of primary and secondary particles with nucleons of the nucleus;
- trajectories of cascade particles are treated “classical” — no interaction among each other;
- the interaction is based on elementary cross sections valid under vacuum. The cross sections are derived from empirical approximations of:
  - $NN \rightarrow NN$  (elastic),
  - $\pi N \rightarrow \pi N$  (elastic),
  - $NN \rightarrow N^*N \rightarrow N\pi N$ ,
  - $NN \rightarrow N^*N^* \rightarrow N\pi N\pi$ ,
  - $\pi N \rightarrow \pi N^* \rightarrow \pi N^*\pi$ ,
  - $N^*N \rightarrow NN$  (delta absorption),
  - $\pi N \rightarrow \pi N$  (charge exchange);
- Pauli blocking, Fermi motion of target and projectile nuclei, pion production, and effects of target mean field are included;
- the nucleus is considered as degenerated Fermi gas of  $ns$  and  $ps$ .

The assumptions for which the above itemized fundamental presumptions (within the INC) are valid are the following:

- the De-Broglie-wavelength  $\lambda$  of cascade particles should be smaller<sup>1</sup> than average distance of nucleons in nucleus ( $\delta \approx 1.3\text{ fm}$ ) and the mean free path length  $L$  in nuclear matter:  $\lambda \ll \delta$ ,  $\lambda \ll L$ ;

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<sup>1</sup> For high energies, this presumption is certainly valid and the interacting nucleons do not “see” the nucleus as whole but as an assembly of individual nucleons bound together by their mean field.

- the duration of elementary impact  $\tau_{\text{int}} \sim r_{\text{int}}/v$  should be smaller than time between two collisions, *i.e.* the radius of the strong interaction should be smaller than mean free path length:  $r_{\text{int}} \ll L$ ;
- the number of participating cascade particles  $N_c$  should be considerably smaller than number of target nucleons  $A_t : N_c \ll A_t$ .

For a more detailed description of the theoretical models, in particular the evaporation models mentioned above, their limits and constraints, please refer to [4–9] and references given therein.

### 3. Nuclear data/databases and the IAEA benchmark of spallation models

Rather than discussing selective experimental data and their comparison to Monte Carlo calculations, in the following, we address the comprehensive benchmark of spallation models which was carried out under the auspices of the IAEA [10–12]. In this benchmark study on model codes for spallation reactions, the code developers have discussed in depth the physics bases and ingredients of the different models in order to understand their strengths and weaknesses. The specifications of the benchmark, including the huge set of selected experimental data to be compared to models is made available online in Ref. [10] — and, therefore, of large value for the spallation physics community. The observables of the data base comprise among others:

- particle cross sections ( $d^2\sigma/d\Omega dE$  of  $n, p, \pi, d, t, {}^3\text{He}$ , alphas, *etc.*);
- multiplicities ( $M_n, M_p, M_\pi, M_d, M_t, M_{\text{He}}, M_{\text{IMF}}$ ), and multiplicity distributions;
- isotope production (isotopic distributions)  $Z, A, \sigma$  [mb], error [mb] in direct and inverse kinematics;
- production cross sections up to 3 GeV (excitation functions);
- isotope production cross sections (isomers).

All data sets in Ref. [10] are linked with the respective reference and can be accessed in EXFOR format and viewed in form of figures. The website and tools to analyse results are fully operational and the idea is to continue the benchmark in a dynamic way, *i.e.* add new experimental data and improved versions of models.

In summary, existing intranuclear cascade-evaporation models are basically capable of describing the spallation reaction process, sets of benchmark data do exist for code validation/improvement and are valuable for the identification of deficiencies of INC/evaporation codes. Nevertheless, high quality nuclear data are still needed. It remains to solve discrepancies between different sets of data and to solve deficiencies of models.

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