DAPNIA/SPhN-99-44

07/1999

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for hybrid systems**

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DAPNIA

*The Experimental Nuclear Physics in Europe (ENPE 99),
Séville (Espagne), June 21-26, 1999*

Comparison between calculations and experimental results on spallation reactions of interest for hybrid systems

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Abstract. Data on proton induced spallation reactions concerning the production of neutrons obtained at SATURNE and of spallation residues at GSI have been compared with two-step models including different Intra-Nuclear Cascades (INC) followed by different evaporation codes. Results and improvements of the codes are discussed.

In the design of Accelerator Driven Systems, it is necessary to precisely predict the energy spectrum and angular distribution of the neutrons produced in the spallation target. This is important for the optimization of the target geometry in terms of useful neutron production and spatial distribution of the neutron flux. The spallation residue production has also to be well understood since these nuclei contribute to the radioactivity or/and could cause structural material embrittlement.

The spallation processes are generally described in two steps: the incident light particle first interacts with the target nucleons through successive nucleon-nucleon hard collisions modeled by the so called Intra Nuclear Cascade (INC), leading to the emission of high energy nucleons. At the end of this stage, the remaining nucleus is left with excitation energy and then de-excites either by evaporation or by fission. The reliability of the available calculation code systems is not yet sufficient to assess all the parameters required to design spallation targets. In this contribution, results of codes are confronted to new data and the physical ingredients inside the models are discussed.

As an exemple, fig. 1 presents neutron double-differential cross-sections in $\text{Pb}(p, xn)X$ reactions at 1200 MeV measured at SATURNE [1]. The histograms are numerical calculations performed with the TIERCE [2] code system developed at Bruyères-le-Châtel. Within TIERCE two different Intra-Nuclear Cascade models followed by the same evaporation-fission model from Dresner-Atchison [3] have been used: Bertini [4] (solid line) and Cugnon [5] (dotted line) models. At 0° , the more realistic parametrization of the $NN \rightarrow N\Delta$ reaction angular distribution [6], introduced in the Cugnon code, solves the problem of the pathologic behaviour

obtained with the Bertini cascade. At higher energy, both models are in quite good accordance with the data between 10° and 85° but Bertini underpredicts the backward angles. Whatever the angle, calculations with the Bertini cascade overestimates the production cross-sections below 20 MeV while the Cugnon model generally leads to a much better agreement.

The averaged neutron multiplicities per reaction have been deduced from the SATURNE neutron cross-sections and compared with results obtained with TIERCE-Bertini and Cugnon codes for the different studied targets: Al, Fe, Zr, W, Pb and Th at three incident energies: 0.8, 1.2 and 1.6 GeV. From this comparison, it can be stated that the Cugnon INC+evaporation is systematically closer to the experiment and is well suited to reproduce the new neutron measurements.

Remaining difficulties with the Cugnon code are illustrated on fig. 2. The description of events with low number of collisions although improved by using new n-p scattering parametrization [6], is still poor. This is mainly visible at forward angles and high outgoing energies. However, the contribution of this part is rather small compared to the total neutron production. Possible improvements are discussed in [5], particularly the introduction of a surface diffuseness is foreseen.

FIGURE 1. Neutron production double-differential cross-sections measured in proton induced reactions on a 2 cm thick Pb target at 1200 MeV [1]. The histograms represent TIERCE calculations [2] using Bertini [4] (full line) or Cugnon [5] (dotted line) cascade model followed by the same evaporation model.

FIGURE 2. Influence of modification of elastic n - p cross-sections (solid curve). The dashed curve is obtained with the old parametrization.

The fact that the Cugnon INC model gives a better agreement with the data than the Bertini one, is likely because it leads to lower excitation energies at the end of the INC stage. Since this model includes explicitly the time development of the cascade, a stopping time to switch towards evaporation has been phenomenologically parametrized [5]. Variation of this time has weak influence on neutron results but can affect strongly the predictions for residue production as illustrated on the upper part of fig. 3 for the coupling of Cugnon INC to the GSI evaporation code [7]. Here a better agreement with the fragmentation data obtained at GSI [8] is obtained when shortening the stopping time (higher excitation energies). However, some modifications inside the evaporation code, lead to a better agreement with the data when using the nominal time (see bottom of fig. 3). The fission bump, not well reproduced, could be a mean to infer the nuclear viscosity [7].

These ambiguities between the respective role of INC and evaporation could be studied in more details in forthcoming exclusive experiments [9]. The correct description of the evaporation and fission products in spallation reactions is still a large challenge as well as the description of the light composite particle production, not correctly described in the present models. Inclusion of a preequilibrium stage between the INC and evaporation steps or the use of a percolation procedure following the INC stage need to be explored [5] to account for the emission of high energy composite particles.

FIGURE 3. Comparison between measured residual mass production and calculations for the system $Pb + p$ at 1 GeV/A [8]. Upper part : two different stopping times of INC coupled with GSI evaporation code [7]. Bottom part : nominal time t_0 and modified evaporation code.

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