REVIEW OF INTERMEDIATE ENERGY NUCLEAR REACTION MODELS FOR ACCELERATOR-BASED NUCLEAR ENERGY APPLICATIONS

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Introduction

The recent interest in the transmutation of radioactive waste using a proton accelerator coupled with a subcritical reactor (e.g. [1]) and in other accelerator-based nuclear energy applications [2] is attended with an increasing importance of a systematic evaluation of relevant nuclear reaction information. The necessary information can be retrieved mainly from available experimental data, nuclear reaction theories and model codes [3], and may eventually be collected and transformed into evaluated data files [4], enabling the closest possible connection between nuclear reaction physics and practical applications. This contribution is restricted to a review of the most frequently employed nuclear reaction models that are relevant to possible future accelerator-based concepts. For the present purpose, it is appropriate to categorize these nuclear reaction models as follows:

- Incident nucleon energies above about 150 MeV. To a good approximation, collisions can be treated as quasi-free scattering processes and the cross sections are predicted rather accurately by the intranuclear cascade mechanism.

- Incident nucleon energies below about 150 MeV. The classical intranuclear cascade model may no longer be adequate and the reaction process is preferably described by optical models for elastic scattering, coupled-channel models for reactions to discrete states and statistical pre-equilibrium and equilibrium models for the continuum part of the spectrum.

In fig. 1, the most probable processes in a proton-nucleus reaction of about 1 GeV are displayed. In the first stage of the reaction, which is an entirely direct process, the incident proton will cause the knock-out of a few intermediate-energy nucleons and ot her hadrons. This int ranuclear cascade stage has ended when a residual nucleus with an excitation energy of several tens of MeV is left. This excitation energy is still so high that a lot of energy may be accumulated on one or a few nucleons, implying the occurrence of direct-like processes. The reaction process has now reached a transitional stage where the equilibration of the excited nucleus starts to take place but where it is still possible for a relatively fast nucleon to be emitted after a few collisions. This is known as precompound or pre-equilibrium emission. Also intermediate-energy fission is possible in this stage. Finally, in the evaporation stage, a compound nucleus is left that evaporates low-energy particles (mostly neutrons). In this stage also competition with fission occurs.
After this intranuclear reaction, the intermediate-energy secondary particles that encounter a new target nucleus will proceed through all stages again and will cause new particles (mainly nucleons) to be emitted from this nucleus. These are called internuclear reactions, taking place in thick targets. The low-energy secondary particles will skip the intranuclear cascade and pre-equilibrium stage and will at once form a compound nucleus with the new target nucleus, from which subsequent evaporation takes place.
This picture implies that for an adequate description of the complete mechanism (i.e. including transport processes), a precise knowledge of nuclear data for incident energies up to the bombarding energy is required.

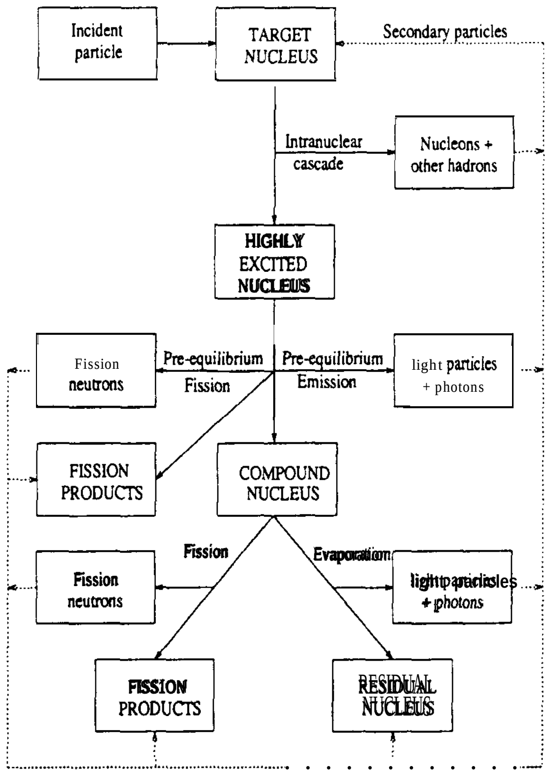

Figure 1: Intermediate-energy nuclear reaction. The solid arrows refer to an intranuclear cascade process (thin target; single proton-nucleus reaction), whereas the dotted arrows represent the internuclear cascade process (thick target; transport processes).

Energies above 150 MeV: The intranuclear cascade picture

In the intranuclear cascade picture, it is imagined that the total reaction process proceeds in two stages. The first step consists of intranuclear cascades of the target nucleons initiated by the incident particle. Several high-energy nucleons, pions and (to a lesser extent) heavier particles are knocked out of the nucleus. In the second stage, the highly excited residual nucleus will undergo fission or it will evaporate a large number of particles and eventually reach the ground state by gamma-ray emission. In the intranuclear cascade model, the classical trajectories of the particles inside the nucleus are followed in coordinate space by means of Monte-Carlo methods. Usually, a simple model is adopted for the nuclear matter, e.g. a Woods-Saxon potential. It is assumed that the collision process consists of two-body interactions only, which are subject to relativistic conservation laws. The numerical simulation of the scattering process is based on free nucleon-nucleon scattering cross sections. If a struck nucleon reaches the nuclear surface and has a kinetic energy that exceeds the binding energy of the nucleon, emission takes place and the energy of the residual nucleus is accordingly reduced. When the kinetic energy is below the binding energy, the nucleon gives its kinetic energy to the nucleus as excitation energy and the evaporation stage begins. A comprehensive exposition of intranuclear cascade and spallation reactions can be found in Ref. [7]. The most frequently used computer code for these processes is HETC [8]: a Monte-Carlo program that calculates nucleon- and meson-induced cross sections on the basis of microscopic nucleon-nucleon and pion-nucleon information. Recently, HETC has been extended with fission [9] and pre-equilibrium processes [10, 11]. In fig. 2 (taken from [12]), some double-differential cross sections as calculated with HETC are compared with experimental data.

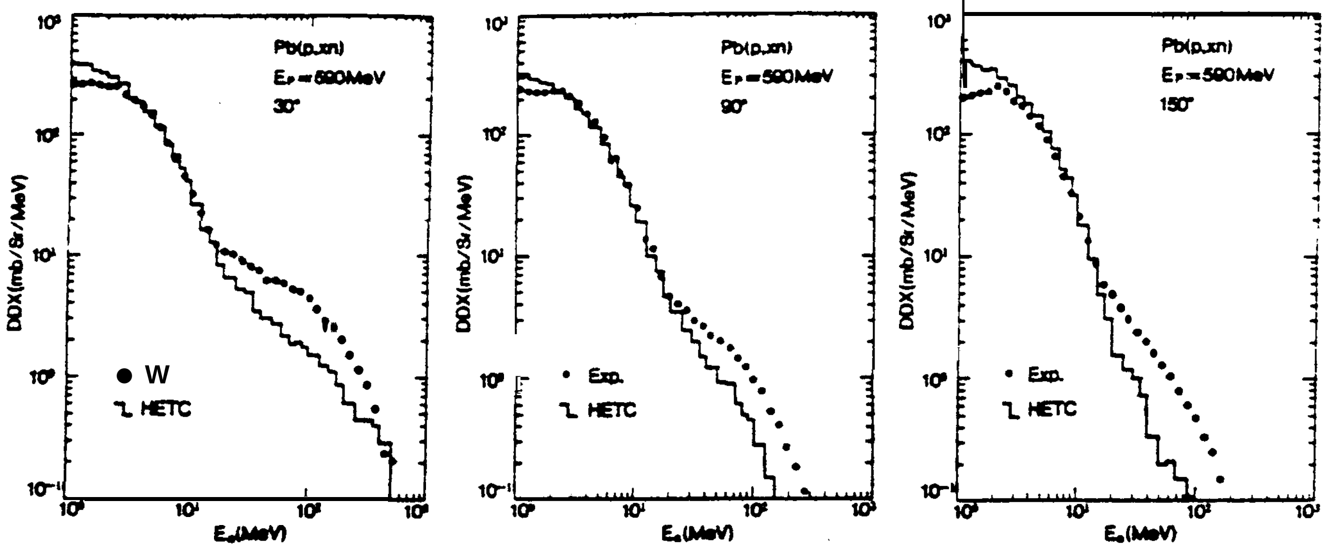

Figure 2: Double-differential cross sections for neutrons at 30, 90 and 150 degrees from a thin lead target for an incident proton energy of 590 MeV. The solid circles are the experimental data and the solid curves represent HETC calculations [12].

Energies below 150 MeV: Direct and (pre)-equilibrium models

For incident energies below about 150 MeV, it may no longer be correct to use a single (intranuclear cascade) model for the prediction of the whole outgoing energy spectrum. Instead, a variety of nuclear models is required, whereby each model has its own appropriate purpose. The following classification can be made:

elastic scattering and reactions to collective states (including giant resonances). The associated cross sections can be described by the optical model and the DWBA or coupled-channels formalism and have been discussed at length in e.g. [13]. A proper analysis of these reactions can be obtained with the coupled-channels code ECIS88 [14].

pre-equilibrium reactions. Pre-equilibrium models provide an adequate description of the high-energy tail (i.e., the region between the evaporation peak and the discrete states) that is observed in the outgoing energy spectra. The reaction process is described in terms of the number of excited particles and holes (the exciton number). At each stage of the reaction there is a non-zero probability that a particle is emitted. If this happens at an early stage, we speak of pre-equilibrium emission. The most widely used semi-classical pre-equilibrium models are the exciton model and the closely related hybrid model (see Refs. [15, 16] for a review). In the exciton model, it is assumed that all possible ways of sharing the excitation energy between different particle-hole configurations with the same exciton number have equal a-priori probability. Instead of following the trajectories of the particles in coordinate stage, one merely traces the temporal development of the exciton number, which changes in time as a result of intranuclear two-body collisions. Although based on quite simple classical principles, the excit on model provides a remarkably good prediction of continuum cross sections. In fig. 3, the high-energy tail of the spectrum is computed using the exciton model. In recent years, the application of quantum-mechanical pre-equilibrium theories (notably that of Feshbach, Kerman and Koonin [17]) has emerged. In these theories, there is a distinction between multi-step direct (MSD) models, which embody a natural extension of direct processes to the continuum, and multi-step compound (MS C) models, which describe the premature emission from an equilibrating nucleus in a quantum-statistical way. Apart from their better physical

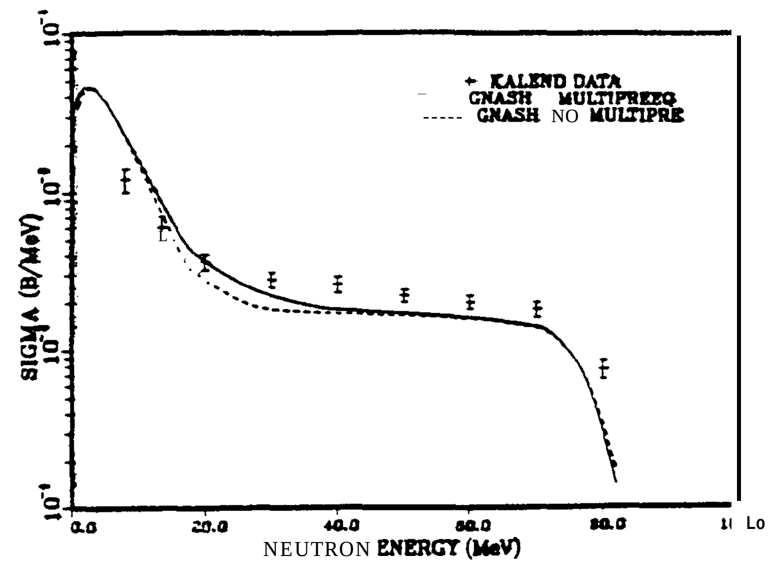

Figure 3: Calculation by GNASH [22] vs. experimental data: ^{27}Al(p,xn) at 90 MeV

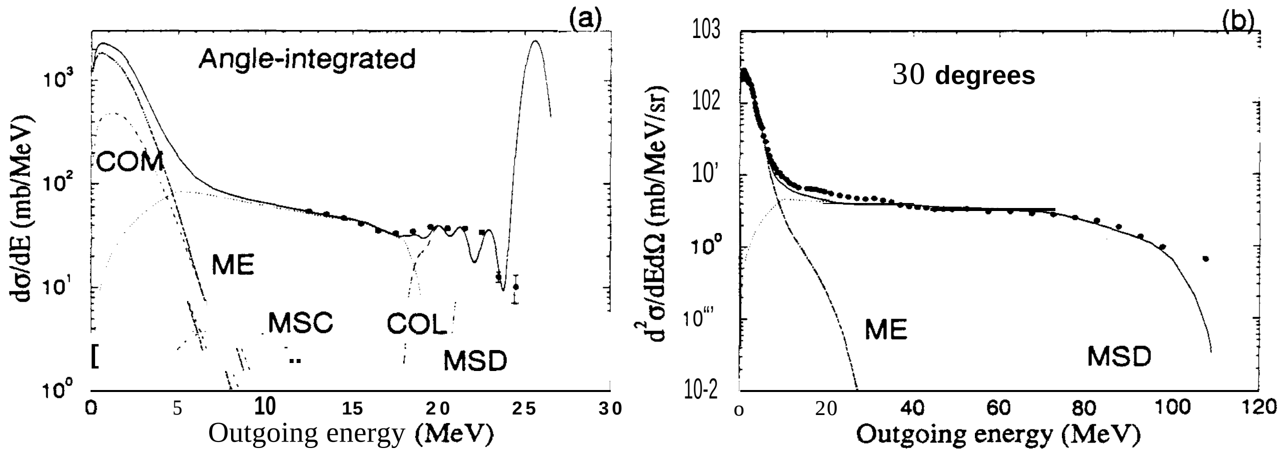

Figure 4: Cross-section calculations [21] by MINGUS vs. experimental data: (a) ^{209}Bi(n,xn) at 25.7 MeV[23], (b) ^{208}Pb(p,xn) at 113 MeV[24]. COL: Collective states, MSD: multi-step direct, MSC: multi-step compound, COM: Compound, ME: Multiple emission.

foundation, the practical advantage of the quantum-mechanical pre-equilibrium models over the semi-classical models is that a good description of *double-differential* spectra can be obtained [18, 19].

equilibrium reactions. Evaporation processes can be predicted by the classical Weisskopf-Ewing model or preferably by the quantum-mechanical Hauser-Feshbach model [16] (which is comput ationally more time-consuming).

- fission. A description of some fission models can be found in [20].

Fig. 4 (taken from [21]) shows some results of the computer code MING US, which combines direct reaction calculations and quantum-mechanical (pre-)equilibrium calculations.

Summary

In this contribution, a brief survey of some important nuclear reaction models that can be helpful for a global analysis of intermediate-energy nucleon-induced reactions has been presented. Essentially, there are two energy regions: the intranuclear cascade regime, where classical Monte Carlo methods are sufficient for a proper description of nuclear reactions and, for energies below about 150 MeV, the regime where more different specific approaches are required. Probably, the best overall picture is obtained if these two different approaches are employed as complementary tools in nuclear data evaluation. A more extensive comparison between the various models has been performed in a recent computer benchmark [25, 26].

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