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On the nucleon effective mass role to the high energy proton spallation reactions

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Abstract

We explore the effect of the nucleon effective mass to the dynamic evolution of the rapid phase of proton–nucleus spallation reactions. The analysis of the relaxation time for the non-equilibrium phase is studied by variations in the effective mass parameter. We determine the final excitation energy of the hot residual nucleus at the end of cascade phase and the de-excitation of the nuclear system is carried out considering the competition of particle evaporation and fission processes. It was shown that the excitation energy depends of the hot compound residual nucleus at the end of the rapid phase on the changing effective mass. The multiplicity of particles was also analyzed in cascade and evaporation phase of the reaction.

The use of nucleon effective mass during cascade phase can be considered as an effect of the many-body nuclear interactions not included explicitly in a treatment to the nucleon–nucleon interaction inside the nucleus. This procedure represents a more realistic scenario to obtain the neutron multiplicity generated in this reaction, which is a benchmark for the calculation of the neutronic in the ADS reactors.

Keywords: Intranuclear cascade; Spallation process; Accelerator-driven systems; Monte Carlo calculation; Neutron yield; Nucleon effective mass

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1. Introduction

The accelerator driven system (ADS) is a type of innovative proposal for a reactor working in sub-critical regime with the highest level of security. When radioactive waste of conventional reactors is taken as the ADS fuel, the spallation reaction transmutes it into a long-lived nuclei, burning the radioactive waste, with some additional gain of power. This device was proposed by Rubbia et al. and has been discussed more recently [1–6]. The system is constituted by a charged particle accelerator with nominal energy necessary to induce spallation reactions in liquid metal target (≈1 GeV for proton on lead reactions).

Nowadays, there are some attempts of constructing such reactors with several final purposes, from basic research up to radio-pharmacological production [7,8]. The description of the beam-target reaction mechanism is the key stone for planning the operation of such reactor. Different ideas of modeling spallation reaction to ADS have been discussed in the last ten years [9–11]. Here, we focus on the proton-lead spallation to discuss the role of nucleon effective mass in the rapid non-equilibrium phase of intranuclear multicollisional processes, namely, the cascade phase.

The nuclear reaction induced by protons has been well described as a two-step process [12,13]. In the first stage, the high energy incident proton interacts with the target nucleus, transferring beam energy to the nuclear system by multicollisional processes in a cascade phase. During this phase, low mass baryonic resonances can be created, as well as nucleons and mesons can be ejected from the nuclear environment. Along the intranuclear dynamics, resonances decay are produced and, according to their half-lives, they decay leading to energetic pions formation, and the escaping particles carries part of the energy initially deposited in the target. The remaining system energy is redistributed in a pre-equilibrium phase through elastic interactions, leading the nucleus to a final thermal equilibrium state.

In the second step of the reaction, the so-called nuclear evaporation phase, the residual nucleus de-excites by evaporating particles in competition with the fission process. The decay chain of hot residual nucleus is developed following different branches, all of them ending in a fission process or leading to a spallation nuclear product. This last phase is most relevant to the neutron generation in the whole reaction course. Only few high energy particles are emitted in the cascade phase (energy value larger than 20 MeV), however they are quite important to the determination of the residual nucleus excitation, which is the key element to the evaporation phase development.

In the present work we explore the effect of consider a effective mass for baryons bounded in the nucleus on results of proton–nucleus spallation reactions at ADS operational energy regime. This reaction is the primary source of neutrons to these reactors this issue was undirectly discussed by mean of the introduction of a momentum or energy dependent in the nuclear mean field potential in the Refs. [14–16]. Here we are explicitly varying the nucleon effective mass to investigate the effect on the residual nucleus excitation energy.

We simulate the proton–nucleus collision for different incident energies in the range of interest for ADS reactors operation. The use of a nucleon effective mass brings a more realistic treatment to in-medium nucleon–nucleon interactions since particles are viewed as "dressed" by some nuclear mean field not explicitly considered in conventional intranuclear processes during the cascade phase. This phase is described by a time-dependent Multicollisional Monte-Carlo (implemented via the MCMC code [17,18]). To describe the spallation reaction we have implemented a Monte Carlo calculation of the whole reaction process. The computational procedure was carried out by means of a numerical FORTRAN code, named Monte Carlo Multicollisional Calculation [19–21]. In the next section, main aspects of the rapid phase are explained, and the