The CRISP Code for Nuclear Reactions

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Abstract. The CRISP package performs the intranuclear cascade process and the evaporation/fission competition resulting in a code that represents a good tool to describe complexes characteristics of the nuclear reactions, and opens the opportunity for applications in different fields, such as medical physics, photonuclear reactions, spallation or fission process initiated by different probes and in Accelerator Driven Systems, where precise description of energetic and angular neutron distribution, neutron multiplicity and spallation products information are needed. In the CRISP model, was included the time-sequence characteristics of the MCMC code and the evaporation/fission competition process model of the MCEF. Also, includes improvements in the code, as the excitation of nucleonic resonances heavier than Delta; the initial nuclear ground state construction according to the Fermi model and Pauli principle; and a more realistic Pauli blocking mechanism. Some consequences of the improvements performed in the code will be discussed, as, e.g., the absence of Pauli Principle violations observed in the occupation number for single-particle bound states, and the absence the lack of the unphysical nuclear boiling. At the present two other reaction channels are being includes, namely, the quasi-deuteron mechanism at energies between 40 MeV and 140 MeV, and the photon hadronization process, which gives rise to the shadowing effect. With these modifications it will be possible to use the CRISP code for energies above 40 MeV up to a few GeV not only for reactions initiated by protons and neutrons, but also by photons. We will describe some of the consequences resulting of these modifications and present some results in order to illustrate the possible applications, for which this package can be used, mainly those related to spallation process involving high-energy protons.

INTRODUCTION

One of the main applications of the Hybrid Reactors (ADS - Accelerator Driven System) is the incineration of transuranics (TRU) by fast neutrons that emerge from a spallation source in a subcritical reactor waste burner [1, 2, 3, 4, 5, 6]. For this application, an accurate description and prediction of spallation reaction is necessary, including all the characteristics concerning spatial and energetic angular distribution, spallation products and neutron multiplicity. To describe the nuclear reactions at intermediate and high energies, Monte Carlo calculations have being used. The CRISP package consider the intranuclear cascade (INC) that occurs during the spallation process in a realistic time-sequence approach in which all particles inside the nucleus can participate in the cascade and the nuclear density fluctuations are naturally taken into account during the process. The occupation number of each single particle level is considered as a function of time and a more realistic Pauli blocking mechanism can be performed. The evaporation of protons and alpha particles are taking into account making possible the correct prediction of fissilities of actinides and pre-actinides. Another implementation is the NN single pion production reaction. This reaction is especially relevant if one is interested in neutron or proton multiplicities, since the creation/emission of pions is directly related with the excitation energy of the residual nucleus. We will present some results obtained with the CRISP package for proton-nucleus reaction at intermediate and high energies. This package was obtained by the coupling of the MCMC and MCEF codes, with the introduction of some improvements, such as a better Pauli blocking mechanism, the formation of a nuclear ground state according the Fermi model which respect the Pauli Principle, the introduction of the most relevant resonant excitation and the NN single pion production channel. The results of interest for ADS development are consistent with the experimental data at different proton energies. More detailed calculations are being performed for studying other features of proton-nucleus reactions and with different targets.

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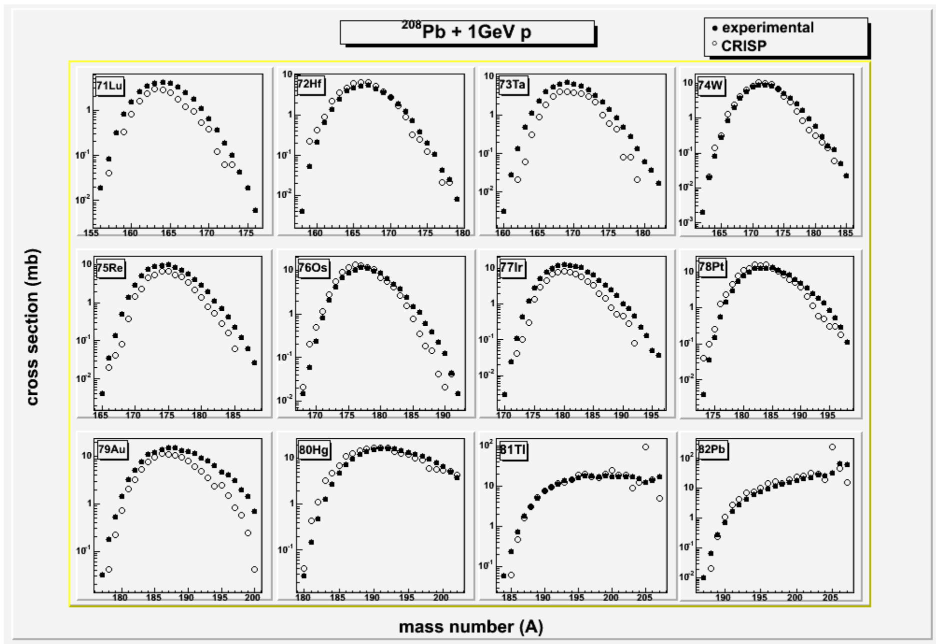

FIGURE 1. The spallation products for 1 GeV protons in Lead. The preliminary CRISP results (open circles) are compared with experimental results (full circles) [14].

SOME ADS MAJOR ISSUES

Concerning the accelerator the intensity and energy of the beam still are open issues and the reliability of the accelerator is an important factor both for Cyclotrons and Linacs. The large quantities of hot materials must be separated with high purity (99.9%). Related to fuels there are the fabrication, the behavior during the burn up and what kind of damage it could suffer. The target issue is where the CRISP code can be utilized. It will help the design, the material choice and the prediction of neutron and spallation products production.

Effects of spallation products on LBE corrosion control are one of the key problems to be investigated. In most hybrid systems a thin windows exists between the incident proton beam and the spallation source needed to protect the vacuum in the accelerator tube and being, at the same time, the first barrier to the spallation target. This window is submitted continuously to the proton irradiation. Among those problems are the radioactivity induced by the spallation products, changes in the chemical composition and embrittlement (Martensitic steels at 90% of Fe).

Some radioactive spallation products are ^{210}Po ($T_{1/2}$ = 138 days) for Bismuth, ^{194}Hg ($T_{1/2}$ = 520 yr) for Mercury and Lead, and ^{148}Gd ($T_{1/2}$ = 74.6 yr) for Tungsten and Lead.

THE CRISP PACKAGE

The CRISP package here developed utilizes an algorithm that describes a many-body intranuclear cascade and evaporation/fission competition process, considering dynamic evaluation of the fermionic multicollisional process and the possibility of neutron, proton and alpha particle evaporation [7, 8]. Fission process can also occur and competing with the evaporation process. Other reaction mechanisms have being included, such as the Pauli blocking, the formation of many nucleonic resonance and the shadowing effect, the last two being important reaction channels for photoabsorption. In the CRISP model, we included the time sequence characteristics of the MCMC code [9], and the evaporation/fission competition process model of the MCEF [10, 11]. The level density parameters utilized are the ones proposed by Dostrovsky [12].

The Pauli blocking mechanism is accounted for by dividing the phase-space into cells, and by imposing the condition that each can be occupied by only one particle. The cell corresponds to a quantum-level, which is determined accordingly to the Fermi gas model. In this approach, due to spin and isospin degrees-of-freedom of the nucleons, we can accommodate up to four nucleons on each level. The cell's availability, for the final state particles, is verified after the analysis of each possible interaction between different particles in the nucleus. If all secondaries can be placed at the correct levels, the

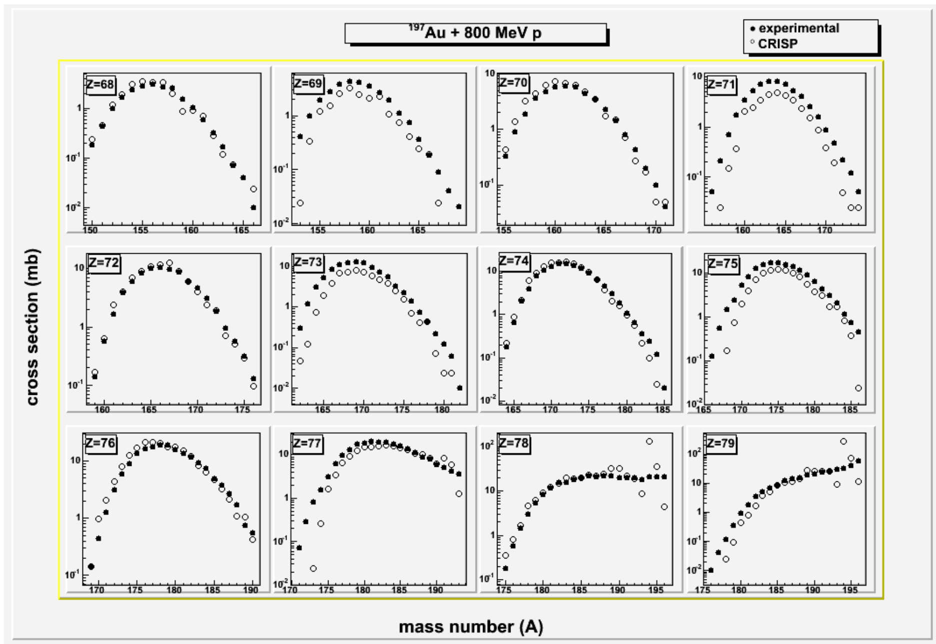

FIGURE 2. The spallation products for 0.8 GeV protons in Gold. The preliminary CRISP results (open circles) are compared with experimental results (full circles) [15].

interaction is allowed, otherwise, it is blocked. This procedure must be performed at every stage of the cascade and also on the construction of the initial ground state nucleus. The Pauli-exclusion principle is incorporated in our model by ensuring that at any step in the intranuclear cascade calculation the number of nucleons, at any level, will not be greater than the limit allowed by this principle.

One of the main advantages of this method, is the elimination of unphysical results such as the violation of the Pauli principle, or the spurious depletion of the Fermi-sphere, which shows up in the form of spontaneous nuclear boiling, leading to the impossibility of keeping the nucleus stable during long times (or many cascade interactions). Also, the incorrect determination of the occupation numbers, and the use of arbitrary cascade stopping-time parameters, could result into events with negative excitation energy.

With the CRISP package we eliminate these undesirable effects and its unphysical consequences, and propitiates a more realistic description of the cascade process, allowing the re-population of the Fermi-sphere by any nucleon inside the nuclear volume during the intranuclear cascade. With these improvements, a physical, energetic criterion for stopping the intranuclear cascade calculation was established, that is, the stopping takes place when all the bound nucleons do not have enough energy to escape from the nucleus.

One implementation is the NN direct single pion production reactions. Pion production in NN collisions is an important process in intermediate-energy nuclear physics. This reaction is especially relevant if one is interested in neutron or proton multiplicities, since the creation/emission of pions is directly related with the excitation energy of the residual nucleus. The channels that are present in the CRISP code are listed bellow:

$$p + p \to p + n + \pi^+$$

$$p + p \to p + p + \pi^0$$

$$n + p \to n\, n\, \pi^+ + p\, p\, \pi^-$$

The NN single pion production threshold is about 300 MeV, and two pions production occurs at about 1000 MeV. The last reaction channel is in an implementation stage.

PRELIMINARY RESULTS

In Table 1, neutron multiplicities for proton induced reactions on Pb at different intervals of energy are given. Our model predictions agree very well with the cascade neutrons (E $\geq$ 20 MeV) and the evaporation neutrons (2–20 MeV) [13]. Also in Table 1 the CRISP results are compared with those obtained with other models.

In Fig. 1 the spallation products obtained after the intranuclear cascade and the evaporation/fission competition process, initiated by the interaction of a 1 GeV proton with the ^{208}Pb nucleus. The results are compared

TABLE 1. Neutron multiplicities in proton-induced reaction on Pb nuclei (second column) compared with the predictions of our model (third column) and those from other models [13].

Neutron energy	Expt.	CRISP	INCL4 KHSv3p	TIERCE Cugnon	LAHET Bertini	LAHET ISABEL	LAHET Bertini–preq
				Pb **E_p=800 MeV**			
0 – 2 MeV		2.9	3.3	4.9	5.61	5.13	5.37
2 – 20 MeV	6.5	6.6	6.8	6.9	8.63	6.63	7.12
> 20 MeV	1.9	2.2	2.5	2.2	1.75	1.92	2.13
Total		12.7	11.7	14.0	16.0	13.7	14.04
				Pb **E_p=1200 MeV**			
0 – 2 MeV		3.3	3.4	5.8	6.35		6.02
2 – 20 MeV	8.3	7.6	8.1	8.9	11.44		9.86
> 20 MeV	2.7	2.6	3.1	2.8	2.45		2.83
Total		13.5	14.7	17.4	20.2		18.7

with those given by experimental data [14]. One may observe that our results are in good agreement with the experimental data.

These results are important for applications, such as, e.g., the studies on accelerator driven systems. More high-energy simulations are being performed in order to obtain and compare multiplicity results up to few GeV energy protons. Similar results are plotted in Fig. 2 for 0.8 GeV protons in ^{197}Au. The results are in agreement with the experimental values.

CONCLUSIONS

The particle multiplicities calculated with CRISP code agrees with the experimental results, giving as good as, or even more precise values than other INC/Evaporation codes. The spallation products parabolas show a good agreement with experimental data indicating the INC and Evaporation/fission processes are being corrected simulated. The CRISP package can be used in ADS target design contributing with the correct prediction of important quantities. As a future work we will include the 2 pions reaction channel, concentrate our efforts to the very beginning of initial interaction in order to correctly simulate the parabolas with high Z and N, and extend the calculations to lighter targets (such as Fe).

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