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High Energy Particle Transport Code NMTC/JAM

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Abstract

We have developed a high energy particle transport code NMTC/JAM, which is an upgrade version of NMTC/JAERI97. The available energy range of NMTC/JAM is, in principle, extended to 200 GeV for nucleons and mesons including the high energy nuclear reaction code JAM for the intra-nuclear cascade part. We compare the calculations by NMTC/JAM code with the experimental data of thin and thick targets for proton induced reactions up to several 10 GeV. The results of NMTC/JAM code show excellent agreement with the experimental data. From these code validation, it is concluded that NMTC/JAM is reliable in neutronics optimization study of the high intense spallation neutron utilization facility.

1 Introduction

NMTC/JAERI97 [1] has been used in combination with MCNP4A [2] as a standard code system at JAERI in the neutronics design study for the spallation neutron source. For the validation of NMTC/JAERI97, we used the experimental data, which have been provided from the ASTE [3] (AGS Spallation Target Experiment) using a mercury target bombarded with protons at incident energies ranging from 1.5 to 24 GeV. Since NMTC/JAERI97 cannot treat the nuclear reactions above 3.5 GeV, it is required to extend the available energy range to higher region. Thus we have introduced the high energy nuclear reaction code JAM [4] into the intra-nuclear cascade part of NMTC/JAERI97 and we have named this new code system NMTC/JAM. In NMTC/JAM code, we have also upgraded the nucleon-nucleus nonelastic, elastic and differential elastic cross section data above 100 MeV by employing new systematics. In this paper, we describe the main feature of JAM and the upgrading work for the cross section data. The comparisons with the experimental data are shown with respect to the thin and thick target systems.

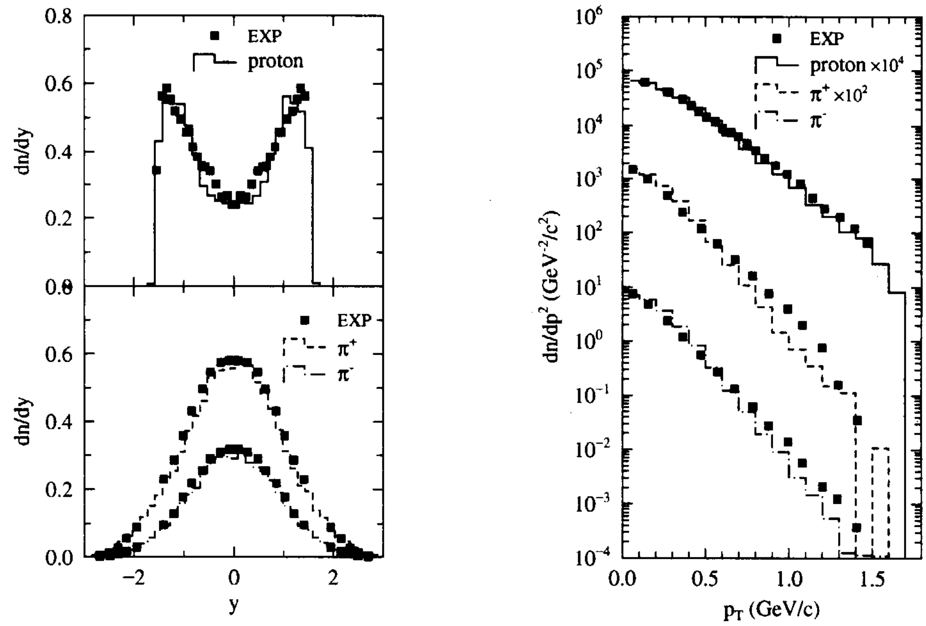

Fig. 1 The rapidity distributions (left panel) and the transverse momentum distributions (right panel) of proton, π^+ and π^- in pp collisions at 12 GeV/c.

2 High Energy Nuclear Reaction Code JAM

JAM (Jet AA Microscopic Transport Model) [4] is a hadronic cascade model, which explicitly treats all established hadronic states including resonances with explicit spin and isospin as well as their anti-particles. We have parametrized all hadron-hadron cross sections based on the resonance model and string model by fitting the available experimental data. Below c.m. energy $\sqrt{s} < 4$ GeV, the inelastic hadron-hadron collisions are described by the resonance formations and their decays, and at higher energies , string formation and their fragmentation into hadrons are assumed. Inelastic cross sections are assumed to be filled up with the resonance formations up to $\sqrt{s} = 3 \sim 4$ GeV. At higher energies, the difference between experimental inelastic cross section and resonance formation cross sections are assigned to the string formation.

We have parametrized the resonance formation cross sections in terms of the extended Breit-Wigner form and used the established data [5] for its decay channels and probabilities. At an energy range above $\sqrt{s} > 4 \sim 5$ GeV, the (isolated) resonance picture breaks down because width of the resonance becomes wider and the discrete levels get closer. The hadronic interactions at the energy range $4 \sim 5 < \sqrt{s} < 10 \sim 100$ GeV where it is characterized by the small transverse momentum transfer is called "soft process", and string phenomenological models are known to describe the data for such soft interaction well. The hadron-hadron collision leads to a string like excitation longitudinally. In actual description of the string formation, we follow the prescription adopted in the HIJING model [6]. The strings are assumed to hadronize via quark-antiquark or diquark-antidiquark creation. As for the fragmentation of the strings, we adopted Lund fragmentation model PYTHIA6.1 [7].

3 Elementary Cross Sections of Hadron-Hadron

For the validation of above prescription of JAM, we compared the results of JAM for the elementary cross sections of hadron-hadron with the experimental data. In Fig. 1 we show the calculated rapidity distributions and the transverse momentum distributions of protons, positive and negative pions for proton-proton collisions at 12GeV/c and also the data from Ref. [8]. The proton stopping behavior and the pion yields are well described by the present model. Within our model, fast protons come from resonance decays and mid-rapidity protons from string fragmentation.

Fig. 2 shows the energy dependence of the exclusive pion production cross sections in *pp* reactions. We compare the results obtained from our simulation with the data [9]. Overall agreement is achieved in these exclusive pion productions. Smooth transition from the resonance picture to the string picture at $E_{cm} = 3 \sim 4$ is achieved since no irregularity of the energy dependence is present in the calculated results.

As for the other elementary cross sections of hadron-hadron, the results of JAM have shown good agreement [4] with the experimental data.

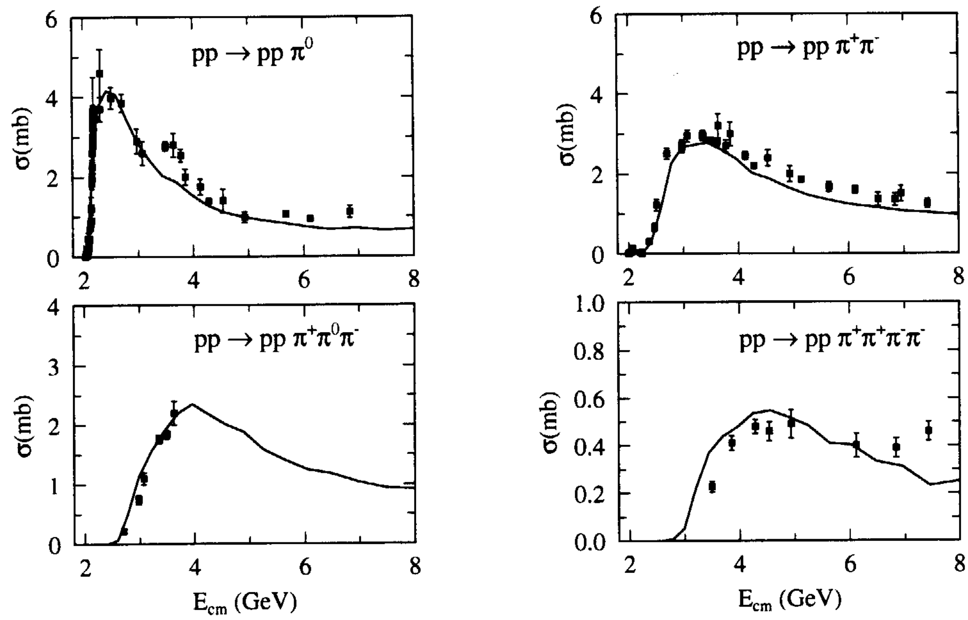

Fig. 2 The energy dependence of the exclusive pion production cross sections for proton-proton as a function of c.m. energy.

4 Upgrade of the Nucleon-Nucleus Cross Sections

We have included the JAM code into the intra-nuclear cascade part of NMTC/JAERI97. For this purpose, it is important to use reliable cross section data of nucleon-nucleus for simulating nucleon and meson transport in medium. In NMTC/JAERI97, Pearlstein's systematic [11] is used for non-elastic and elastic cross sections of neutron-nucleus reactions, while for proton-nucleus reactions, elastic collision is not considered, and non-elastic cross section is determined by Bertini model [12] (which is the intra-nucleus cascade model used in NMTC/JAERI97). We have then made new systematics based on Pearlstein's for proton as well as neutron nucleus cross sections.

In Fig. 3, we plot the results of new systematic (bold solid lines) for the non-elastic cross section of p+C and p+Pb. In the same figure, we also show the results of LA150 [13] (gray lines), the original Pearlstein's systematics (dashed lines), and the simulation results of Bertini model (solid lines up to 3.5 GeV) and JAM code (solid line above 3.5 GeV). The present results well follow the experimental data and also LA150 data, while the results of the original Pearlstein's systematics overestimates the data below 100 MeV.

The connection of the simulation results between Bertini and JAM is not smooth and in the low energy region, the results of Bertini are too high. This is one of the reason to create present new systematics.

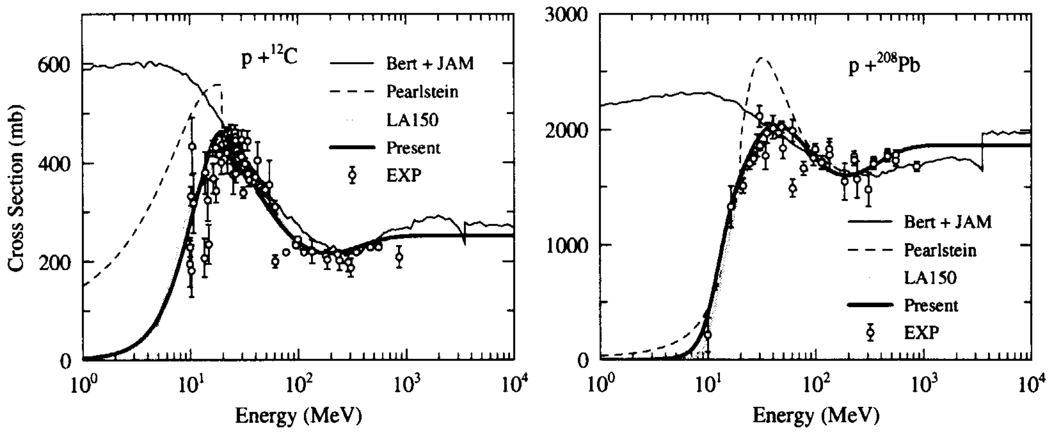

Fig. 3 Non-elastic cross section of p+C (left panel) and p+Pb (right panel).

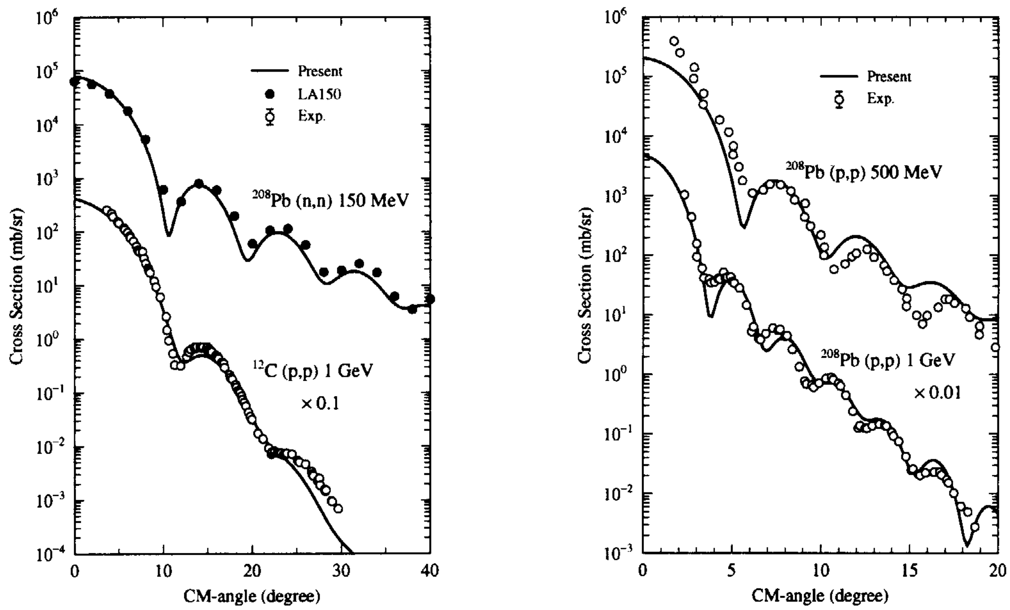

Fig. 4 Angular distribution of the elastic cross sections.

We have also created the new systematics based on the Pearlstein systematics for nucleon-nucleus elastic angular distributions. Fig. 4 shows the results of the new systematics of the angular distribution of the elastic cross sections. We compare the present results with the experimental data and LA150. The present results well reproduce the experimental data for all over the incident energies.

5 Comparison with Experimental Data: Thin Target

By making use of these elementary cross sections, we have calculated the DDX of produced particles from proton induced reactions on thin targets. In Fig. 5, we plot the invariant transverse mass distribution of proton (left panel), π^- (middle panel), and K^+ (right panel) from proton on thin Au target reaction at 13.7 GeV. The results of NMTC/JAM (histograms) and data [10] are plotted for each rapidity bin quoted in the figure. For all ejectiles, the results of NMTC/JAM agree well with the experimental data [10]. The agreements are also shown in the other targets of Be, Al, and Cu in Ref. [4]

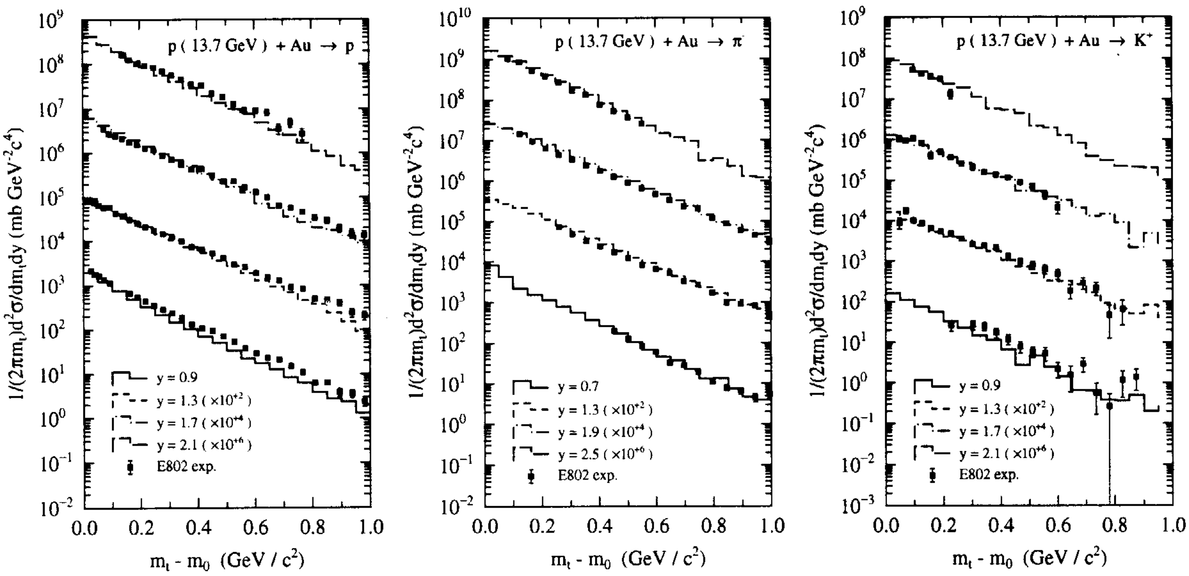

Fig. 5 Invariant transverse mass distribution of proton (left panel), π^- (middle panel), and K^+ (right panel) from proton on thin Au target reaction at 13.7 GeV.

6 Comparison with Experimental Data: Thick Target

We have applied NMTC/JAM to thick target analysis. Fig. 6(a) and (b) shows the distribution of the ^{209}Bi(n,4n)^{206}Bi and ^{209}Bi(n,5n)^{205}Bi ((a) left panel), ^{27}Al(n,α)^{24}Na, ((b) right panel) reaction rates along the cylindrical surface of 20 cm diameter and 130 cm long mercury target bombarded with 1.6, 12 and 24 GeV protons at AGS [3]. As seen in Fig. 6(a), the results of NMTC/JAM reproduce the experimental distribution quite well at the positions far from 30 cm in the longitudinal distance. As the foil position becomes closer to the incident beam point, the agreement becomes worse. Since the ^{209}Bi(n,4n)^{206}Bi and ^{209}Bi(n,5n)^{205}Bi reactions are sensitive to the neutrons with energies 30 to 40 MeV, these neutron yield may be underestimated by the NMTC/JAM calculation. In the same figure, we have plotted the results of NMTC/JAM (dashed lines) with only nucleons and pions as transport particles. The increases of the reaction rate from the dashed lines to the solid lines are, therefore, due to the effects of the neutrons produced via the transport of the other secondary mesons and barions. About 10 $\sim$ 20% enhancement by this effect is found on the total neutron yield at these energies. As shown in Fig. 6(b), good agreement is obtained between the present NMTC/JAM calculation and the experimental data for the ^{27}Al(n,α)^{24}Na reaction at proton energies of 1.6, 12 and 24 GeV, respectively. In the actual calculations, the MCNP-4A code was employed for the transport calculation of neutrons with energies below 20 MeV. we have also used the Bertini model for the intra-nuclear cascade part below 3.5 GeV, and JAM above 3.5 GeV and used the in-medium nucleon-nucleon cross sections [1] in Bertini model. This connection between Bertini and JAM models is due to the reduction of the calculation time. The cpu time of JAM calculation is about ten times longer than that of Bertini model, and the results of the cross sections calculated by both models are almost the same below 3.5 GeV.

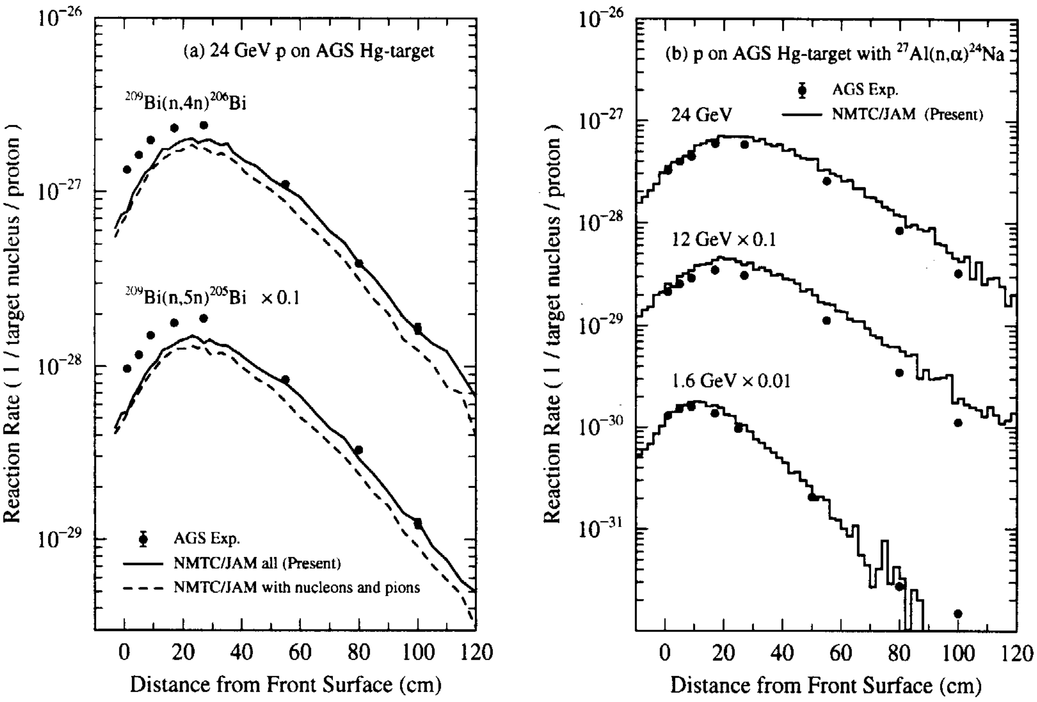

Fig. 6 Reaction rates along the cylindrical surface of 20-cm diameter and 130-cm long mercury target bombarded high-energy protons. (a) ^{209}Bi(n,4n)^{206}Bi and ^{209}Bi(n,5n)^{205}Bi reactions for 24 GeV proton incidence. (b) ^{27}Al(n,α)^{24}Na reaction for 1.6, 12 and 24GeV proton incidence.

7 Summary

We have developed a nucleon-meson transport code NMTC/JAM, which is an upgrade version of NMTC/JAERI97. The available energy range of NMTC/JAM is , in principle, extended to 200 GeV for nucleons and mesons including the high energy nuclear reaction code JAM for the intra-nuclear cascade part. JAM is a hadronic cascade model, in which we have parametrized all hadron-hadron cross sections based on the resonance model and string model by fitting the available experimental data. For the validation of JAM, we have compared the elementary hadron-hadron cross sections and the particle production cross sections from thin target with the experimental data. The experimental data are well described by JAM for the energy range up to several ten GeV. For the transport part of NMTC/JAM, we have upgraded the nucleon-nucleus non-elastic and elastic cross sections by employing the new systematics. We have compared the calculations by NMTC/JAM code with the experimental data of thick targets measured at AGS for proton induced reactions up to several 10 GeV. The results of NMTC/JAM code show excellent agreement with the experimental data. From these code validation, NMTC/JAM will enable us to carry out reliable neutronics optimization study of the high intense spallation neutron utilization facility.

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