Introduction

The last decade brought spectacular advances in astrophysics of cosmic rays (CRs) and γ-ray astronomy. Launches of missions that employ forefront detector technologies were followed by a series of remarkable discoveries even in the energy range that deemed as well-studied. Among those missions are the Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics (PAMELA), the Fermi Large Area Telescope (Fermi-LAT), the Alpha Magnetic Spectrometer-02 (AMS-02), NUCLEON experiment, CALorimetric Electron Telescope (CALET), Dark Matter Particle Explorer mission (DAMPE), and Cosmic-Ray Energetics and Mass Investigation (ISS-CREAM). Outstanding results have been also delivered by mature missions, such as the Cosmic Ray Isotopeme Spectrometer onboard of the Advanced Composition Explorer (ACE-CRS) operating for more than two decades, and by Voyager 1, 2 spacecraft, currently at 151 AU/126 AU from the Sun, respectively.

The modern technologies employed by many of these missions have enabled measurements with unmatched precision, enabling searches for the subtle signatures of dark matter (DM) and new physics in CR and γ-ray data. The reached level of precision demonstrates that we are on the verge of major discoveries.

Interpretation of CR data, observations of the diffuse photon emissions, and search of new physics are critically dependent on the accuracy of the isotopic production cross sections. The latter are the centerpiece of any propagation model, dependent on the accuracy of the isotopic production cross sections. The most recent version, INCL.6.4, has replaced binary cascade as default model choice in GEANT4.

The Cascade-Exciton Model (CEM) [6] describes the INC using the time-independent Dubna cascade model [7] that makes use of 3D geometry for all cascades. All the INC models are followed by pre-equilibrium and equilibrium models, describing intermediate and slow processes of nucleus de-excitation, respectively. However, INCL.6.4 does not consider pre-equilibrium stage and is directly coupled to equilibrium models GEM [8] in PHITS transport code [9] or ABLA [10] in GEANT4.

PEANUT of FLUKA and CEM consider their own sequences of models. PEANUT is using modified hybrid excitation model of Blann [11] for pre-equilibrium part and Weisskopf-Evning statistical model [12] for evaporation. For light nuclei Fermi break-up model is implemented. In CEM, Modified Exciton Model [13] and GEM equilibrium model are employed, Fermi-break-up is also considered.

Current state

Interactions of nucleons and particles with nuclei in the energy range from several dozens of MeV to several GeV/nucleon are usually described by a combination of Intracnuclear cascade (INC), pre-equilibrium, and equilibrium models. More sophisticated Quantum Molecular Dynam-ics (QMD) models, due to their complexity, did not spread much to really compete with INC models. More sophisticated Quantum Molecular Dynamics (QMD) models, due to their complexity, did not spread much to really compete with INC models, although they generally show better results at low energies. INC models, due to their complexity, did not spread much to really compete with INC models. Most complete description of nuclear reactions in the range of 10s MeV is provided by TALYS [14], although it has constraints for atomic masses <10 and for energies <200 MeV. A comparison of evaporation mechanisms manifest in favor of Hauser-Feshbach approach in the intermediate energy region. This led to attempts of combining INC stage with Hauser-Feshbach statistical emission. Such codes as CASCADEX (combining CASCADE/IPPE realizing Dubna INC model with TALYS 1.0) [18], cascadeXO (CASCADE/IPPE + TALYS 1.95), cemcas (CEM03 + TALYS 1.95) demonstrate better accuracy for certain reactions. However, there is no unique model that can describe the cross section data for all nuclei up to several GeV/nucleon. Therefore, it is reasonable to represent the excitation functions as best estimate value accompanied by an uncertainty band.

New Facility

The major obstacle in improving an accuracy of the nuclear codes is the scarcity of the available measurements (Fig. 1). We are aiming at using the NICA facility (Nuclotron-based Ion Collider Facility, https://nica.jinr.ru/) – a new accelerator complex at the Joint Institute for Nuclear Research (JINR, Dubna, Russia). NICA will provide variety of beam species from p to Au ions. Heavy ions will be accelerated up to kinetic energy of 4.5 GeV/nucleon, protons – up to 12.6 GeV. Measurements of cross sections in the energy range from several dozens of MeV up to several GeV/nucleon will be conducted using proton and ion beams and thin targets. Besides, NICA can be used for studies of secondary neutron and γ-ray emission – of interest for simulations of the radiation environment at the rocky surfaces of planets and asteroids. New data will be used to tune models of nuclear reactions and for astrophysical applications.

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