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Integrated simulation of fragmentation, evaporation, and gamma-decay processes in the interaction of cosmic-ray heavy ions with the atmosphere using PHITS

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The Cosmic ray heavy ions interacting with the nuclei in the atmosphere produce various secondary particles such as nucleons, nuclear clusters, fragments, mesons, and prompt gamma-rays. Some of the recent experiments focus on the coincidence measurement of the prompt gamma-rays emitted in the interaction of heavy ions and atmosphere. A number of simulation codes have been developed for prediction of cosmic ray reactions. However, very few can simulate event-by-event prompt gamma-ray emission because it is necessary to determine the isotopic species produced in each reaction and to calculate the internal transition intensity between discrete levels based on the nuclear structure data. The excitation energy of heavy ion fragments is predominantly emitted as prompt gamma-rays. Therefore the gamma-rays from energetic projectile fragments are Lorentz-boosted and observed as energetic gamma-rays in the laboratory frame. Because the Lorentz gamma-factor of each fragment can be large, the gamma-rays reach GeV range. In order to consistently calculate the fragmentation reactions leading to gamma-ray emission, reactions models were revised and implemented to the general-purpose radiation transport code PHITS. In this work, the non-equilibrium phase of the projectile-target nuclear reaction, the equilibrium decay phase, and the gamma de-excitation phase are simulated by the Jaeri Quantum Molecular Dynamics model (JQMD), the generalized evaporation model (GEM), and ENSDF-Based Isomeric Transition/isomEr production Model (EBITEM), respectively. Recently, JQMD was revised to precisely calculate peripheral collisions in addition to central collisions. EBITEM is a gamma-decay reaction model, which uses the nuclear structure data taken from ENSDF and the angular momenta of the residual nuclei after the statistical decay. Because all these models are event generators, secondary particle emission was calculated in event-by-event basis. The produced secondary particles were Lorentz-transformed to the laboratory frame. Prompt gamma-ray emission was simulated in typical conditions such as 10 AGeV Oxygen interactions with Nitrogen. The calculated gamma-ray energy spectra showed sharp peaks corresponding to particular internal transition paths. This study shows that the combination of JQMD+GEM+EBITEM, particularly de-excitation simulation based on the nuclear structure data, is useful for event-by-event calculation of prompt gamma-rays emitted in the interaction of cosmic ray heavy ions and the atmosphere.

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