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INC MODEL INTERPRETATION OF THE PROTON INDUCED RESIDUAL NUCLIDE PRODUCTION CROSS SECTIONS BELOW 2 GeV*

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Abstract: For the purposes of interpreting the abundances of various isotopes in meteorites or on lunar and planetary (e.g., Martian) surfaces exposed to fragmentation by cosmic rays, Webber et al. recently reported the measured total elemental and isotopic cross sections with heavy ions as projectiles on H, He, and C targets with beam energies of 0.33 - 1.7 GeV/nucleon. We employ the INC model to predict the fragmentation of the heavy ions in a hydrogen target with the inverse reaction process: proton bombardment of a heavy-ion nucleus leading to spallation products. Charge-changing and mass-changing cross sections are calculated for proton bombardment of an ^{56}Fe target with beam energies ranging from 0.33 to 1.88 GeV. Total Z-changing and A-changing cross sections in the energy range 0.6 to 1.88 GeV are in excellent agreement with the corresponding experimental data of Webber et al. and Westfall et al., while the agreement below 0.6 GeV proton energy is not as good. The general trend of the Z-changing cross sections are reproduced by the model calculations at each proton incident energy. The interaction of 200-MeV protons with synthetic Stony meteorite samples was undertaken to explain radionuclide production in a cosmic-ray environment. The BNL Linac 200-MeV-proton beam was used to irradiate synthetic Stony Meteorites to simulate cosmic-ray exposures corresponding to 6.4 and 16.4 million years. Each irradiated sample was analyzed with the help of a high-resolution gamma-ray spectrometer for long-lived radioisotopes. The intranuclear cascade code HETC was employed to simulate the 200-MeV proton bombardment on the meteorite samples to predict the radionuclides ^{7}Be, ^{22}Na, ^{46}Mn, and ^{56}Co produced in the experimental investigation. Except for the case of ^{7}Be, the agreement between experimentally measured dpm rates is in good agreement with the HETC predicted production rates.

A. Thin-target residual nuclide production cross sections.

Webber et al.[1] have measured the individual and total charge- and mass-changing cross sections with ^{56}Fe beam on hydrogen, helium, and carbon targets in the 330-1700 MeV/nucleon energy range. Westfall et al.[2] measured the charge-changing cross sections for the reaction ^{56}Fe + p. The reaction ^{56}Fe + p and p + ^{56}Fe which may be considered equivalent in that in both these reactions, only binary collisions account for the proton-nucleus interactions. In the case of nucleon-nucleus collisions the lack of coherence in the interaction process makes it possible to rely on the physics of binary collisions. In the present study we employ the Intranuclear cascade (INC) Model, which is based on binary collisions, to investigate the interaction of protons with ^{56}Fe target below 2000 MeV/nucleon energy. Until the advent of a full quantum mechanical description of the nucleon-nucleus and nucleus-nucleus collisions in the intermediate to high-energy region the INC Model may be used to predict most of the observables measured in proton-induced reactions.

We have used the Intranuclear-Cascade-Evaporation code of Bertini[3] to calculate the individual charge-and mass-changing cross sections for the interaction of 330 to 2000 MeV protons with an ^{56}Fe target. Monte Carlo techniques are used to simulate the intranuclear cascade and subsequent evaporation of the excited residual nuclei. During the cascade stage both the nucleon-nucleon and pion-nucleon interactions are considered. The equilibrated residual nuclei are allowed to de-excite by the emission of proton, neutron, deuteron, triton, helium-3 and alpha particles.

Due to lack of space we cannot present detailed comparison of experimental and calculated results. At each incident proton energy the general trend of the measured charge changing cross section as a function of Z is reproduced by the INC Model calculations. The agreement between theory and experiment is good in the case of Ca, K, Ar and S production cross sections as a function of proton

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instrumentation contained a high-purity germanium (HPGe) detector (Tennelec ER-28200) with a volume of 155.3 cm^3.

The detector was calibrated with a 1-μCi mixed-radionuclide gamma standard prepared by Analytics, Inc. The standard was prepared by spiking a 7-gram sample of synthetic meteorite with an aliquot of a master radionuclide source containing 10 gamma energies ranging from 89 KeV (^{109}Cd) to 1836 KeV (^{88}Y). This calibration was based on a source confirmed by the National Institute of Standards and Technology to ± 5%.

Again, due to lack of space we cannot present a detailed comparison of experimental data with the model predicted results. The predicted values, with the exception of those of ^{7}Be, are in good agreement with those determined experimentally. The ^{7}Be results are consistently lower than those found experimentally. This is expected since the production of low-mass nuclei, such as the ^{7}Be is principally from fragmentation of heavier nuclei. Fragmentation effects were not included in the theoretical model.

The ^{22}Na, ^{46}SC, ^{54}Mn and ^{56}Co predictions are within range of the experimental results over the depth of sample examined. The experimental results indicate little depth dependence, while the theoretical predictions apparently call for slight increases with depth within the considered 8 cm length of the meteorite sample. However, the variations with depth are not significant except for ^{22}Na. In the case of the ^{46}Sc, ^{54}Mn and ^{56}Co predictions vary no more than 2 S.D. over the range of depth. The ^{22}Na prediction calls for a strong increase with depth which does not show up in the present experimental analysis.

When the experimental and the predicted values are averaged over the volume of each sample an even better correspondence occurs. This is shown in Fig. 2.

Currently simple elemental samples Al, Si, Fe and Cu are being exposed to 200 MeV proton beam at BNL-REF facility. The experimental measurement of the long-lived radio isotopes will enable us to identify the target material responsible for the production of a particular radio nuclide.

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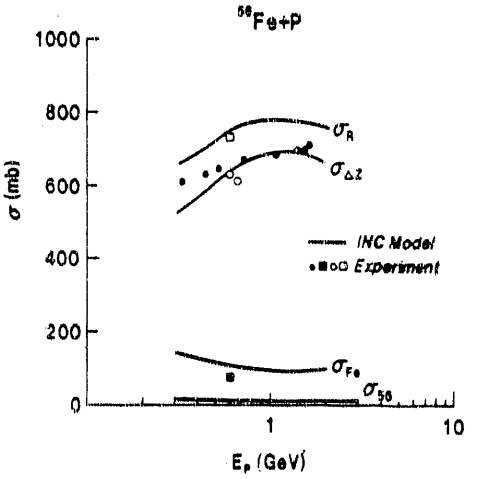

Fig. 1: Reaction cross section σ_R total charge changing cross section $\sigma_{\Delta Z}$; cross section for the production of Fe isotopes and ^{56}Fe production cross section. The filled and unfilled symbols correspond to experimental data at 600 MeV. The open circles represent the sum of the measured individual Z-changing cross sections measured by Webber et al., while filled circles correspond to the total charge changing cross sections quoted by Webber at al. (Phys. Rev.C41, (1990)) These cross sections do contain the contribution due to directly measured Z-changing cross sections as well as the component due to the low z element produced in the proton induced reaction on ^{56}Fe.

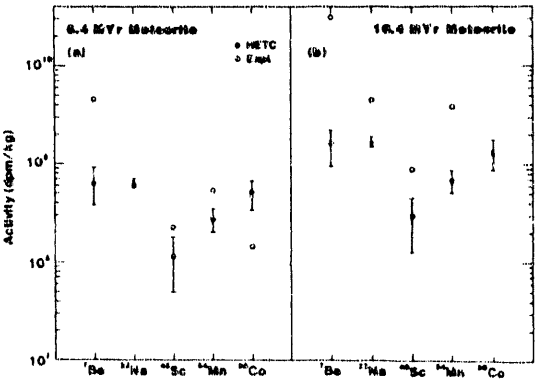

Fig. 2: Total production of radionuclei in target, as a result of irradiation with 200 MeV protons, equivalent to 6.4 m.y. (A) and 16.4 m.y. (B) cosmic-ray exposures.

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