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## Abstract

The proton spectrum over the angular interval from 0 - 10 mrad from the interactions of 29.4-GeV N on C has been calculated. The differential cross section for the emission of protons indicates that there is a significant number of emitted protons with energies greater than the energy per nucleon of the incident projectile (2.1 GeV). A brief description of the calculational method is included.

It has been shown that the absolute value of experimental energy-angle-correlated nucleon spectra from continuum-state transitions involving nucleons with energies of about 1 GeV on complex nuclei can be reasonably reproduced by the method of intranuclear cascades.[1-3] In this method, the incident nucleon interacts initially with one of the bound nucleons of the nucleus in a "quasi-free" interaction. The collision products from this interaction, which might include pions, move through the nucleus and interact with other bound nucleons in the same manner, and the process is repeated (building up a cascade of particles) until all of the collision products escape or are absorbed by the nucleus. This method has been extended to the interaction of heavy ions where the reaction is treated as the interaction of two Fermi gasses. The model is used to study the interactions of 29.4-GeV N with C nuclei and to calculate the proton spectrum in the angular interval from 0 - 10 mrad.

The heavy-ion reaction then is envisioned to take place as follows: During the passage of the incident heavy ion (projectile) through the target, those nucleons of the projectile that are in the region of overlap undergo quasi-free reactions with the individual nucleons of the target. A cascade is thereby generated simultaneously in both target and projectile. The nucleons that have been jarred free of the binding forces in either the target or projectile and that also manage to survive capture during the development of the cascade escape from the target and projectile. They are emitted as free nucleons in various directions and with a variety of energies. After completion of the cascade, the remaining fragments of the projectile and of the target move off in highly excited states emitting evaporation particles until sufficient excitation energy is lost to stop the evaporation process.

The present version of the heavy-ion-collision model only approximates the feature of the simultaneous cascades in both projectile and target. To this end, we first permit the projectile, moving with velocity $\bar{V}$, to impinge upon a target that is stationary in the laboratory frame of reference. Cascades are allowed to develop only in the target. This is called the "forward" reaction. Then the target, moving with velocity $-\bar{V}$, is made to impinge upon the projectile, which is taken to be stationary, and cascades are then permitted only in the projectile. The directions and energies of all particles thus calculated in this "inverse" reaction are transformed to their corresponding values in the frame of reference of the forward reaction, i.e., in the laboratory frame. The results from the forward and inverse reactions are then each weighted by one-half.

The general physical properties that are simulated for the nuclei of every target and every projectile are as follows: The nucleons making up the nucleus are clustered closer together near the center of the nucleus than on the edges. The density distributions are thus approximations to measured, Fermi-type charge-distribution functions.[4] The outer radius of each nucleus is taken to be that radius at which the measured charge distribution function falls to a fraction of its value at the center.[5] The nucleons bound in the nucleus are in constant motion with zero-temperature, Fermi energy distributions, which are determined by their local densities. Attractive single-particle potentials are assumed to exist in the nucleus, and these are made to vary in strength with the Fermi energy. An approximation to account for exclusion effects in all reactions is incorporated. Further details on the nuclear properties are given elsewhere.[6]

Briefly, the calculation, which employs Monte Carlo techniques, proceeds as follows:[5]

1. A center-to-center impact parameter, modified crudely for Coulomb effects, is randomly selected from a uniform distribution over the area of a circle whose radius is the sum of the target and projectile radii. The coordinate system of the laboratory frame of reference is located at the center of the target with the z axis in the direction of the incident projectile. Approximate calculations are used to alter the direction of the incident heavy ion to account for Coulomb deflection.

2. Each nucleon in the projectile is assigned a position inside the projectile and is given an internal energy. The positions and energies are randomly selected from the density and Fermi-energy distributions described above. The internal energies do not change the incident kinetic energy (taken to be the kinetic energy per nucleon of the heavy-ion reaction).

3. Trajectories for each nucleon of the projectile are calculated, all initially parallel to each other, with x and y positions determined by steps 1 and 2. Depending on the impact parameter selected, some of these nucleons will miss the target completely, while some will pass through the target but will not collide (because of target transparency). The remaining fragment of the projectile consists of all of these uncollided nucleons, and it also consists of holes interspersed throughout the fragment. The holes result from the removal of those nucleons of the incident projectile that have collided.

4. For each nucleon that collides, an independent cascade is developed in the target. Some of the cascade neutrons and protons (and also $\pi$-mesons) escape with various energies and directions. The kinetic energy assigned to each nucleon of the incident projectile is the incident kinetic energy per nucleon of the heavy-ion reaction. The binding energy of each nucleon

of the projectile that collides is subtracted from the reaction energy of the initial collision. The binding energies are calculated from the assigned internal energy of each nucleon.

5. The excitation energy remaining in the projectile fragment is calculated from the holes therein, while that for the target is calculated from a kinematic energy balance.

6. Conservation of total energy and momentum is invoked in carrying out the relativistic kinematics calculations that determine the directions and kinetic energies of the fragments of the projectile and target. An angular distribution for the projectile fragment suggested by experimental evidence is employed;[7] i.e., it is assumed that the projectile fragment is isotropically distributed in a system moving with velocity $\bar{V}$ of the initial projectile.

7. As the excited projectile and target fragments move away from the interaction site, they are made to evaporate particles until their excitation energy is lost. The evaporation from the fragment of each particle is calculated in the rest system of the fragment, where isotropic emission of the particles is assumed. The laboratory energy of each particle is calculated by a transformation back to the laboratory system. The change in momentum of the fragment following each evaporation is taken into account.

8. Steps 1-7 are repeated several hundred times in order to properly sample from the distributions employed.

9. The inverse reaction described above is calculated by repeating steps 1-8, while interchanging the roles of target and projectile, and the results are transformed back to the laboratory frame of reference. However, the fragment of the stationary projectile in the inverse reaction is given the same angular distribution as it has in the forward reaction.

The predicted proton spectrum at forward angles from 29.4-GeV N on C collisions is shown in Fig. 1. There are two peaks predicted at high energies. The peak centered at 1.7 GeV is made up primarily of cascade or direct-interaction protons from the forward reaction (84%) with the remainder consisting of cascade protons from the inverse reaction (10%) and evaporation protons from the projectile in the inverse reaction (6%). The peak centered at 2.3 GeV consists mainly of protons evaporated from the projectile in the forward reaction (56%), with cascade and projectile evaporation protons from the inverse reaction contributing the remainder (16 and 28%, respectively).

The peak at 1.7 GeV is the "quasi-free" peak from the direct interactions of the nucleons of the projectile with those of the target. The peak is located at a smaller energy than expected (expected at ~ 2.1 GeV at these angles) because of exclusion effects.

It is both interesting and important to note that the cross section for the emission of protons with energies greater than the energy per nucleon of the incident projectile (2.1 GeV) is quite significant. Experimental verification of the shape of the proton spectra is important in order to guide the theoretical approaches. Other attempts at heavy-ion calculations, which are similar to these but which do not include the inverse reaction, yield proton spectra that vanish at energies greater than the energy per nucleon of the incident projectile.[8]

There are obvious deficiencies in the present model, but they are not expected to have a significant bearing on the high-energy proton spectrum. Two of these deficiencies are the neglect of the effects of nuclear depletion and the neglect of angular momentum. Efforts at estimating the magnitude of these effects on heavy-ion reactions are in progress.

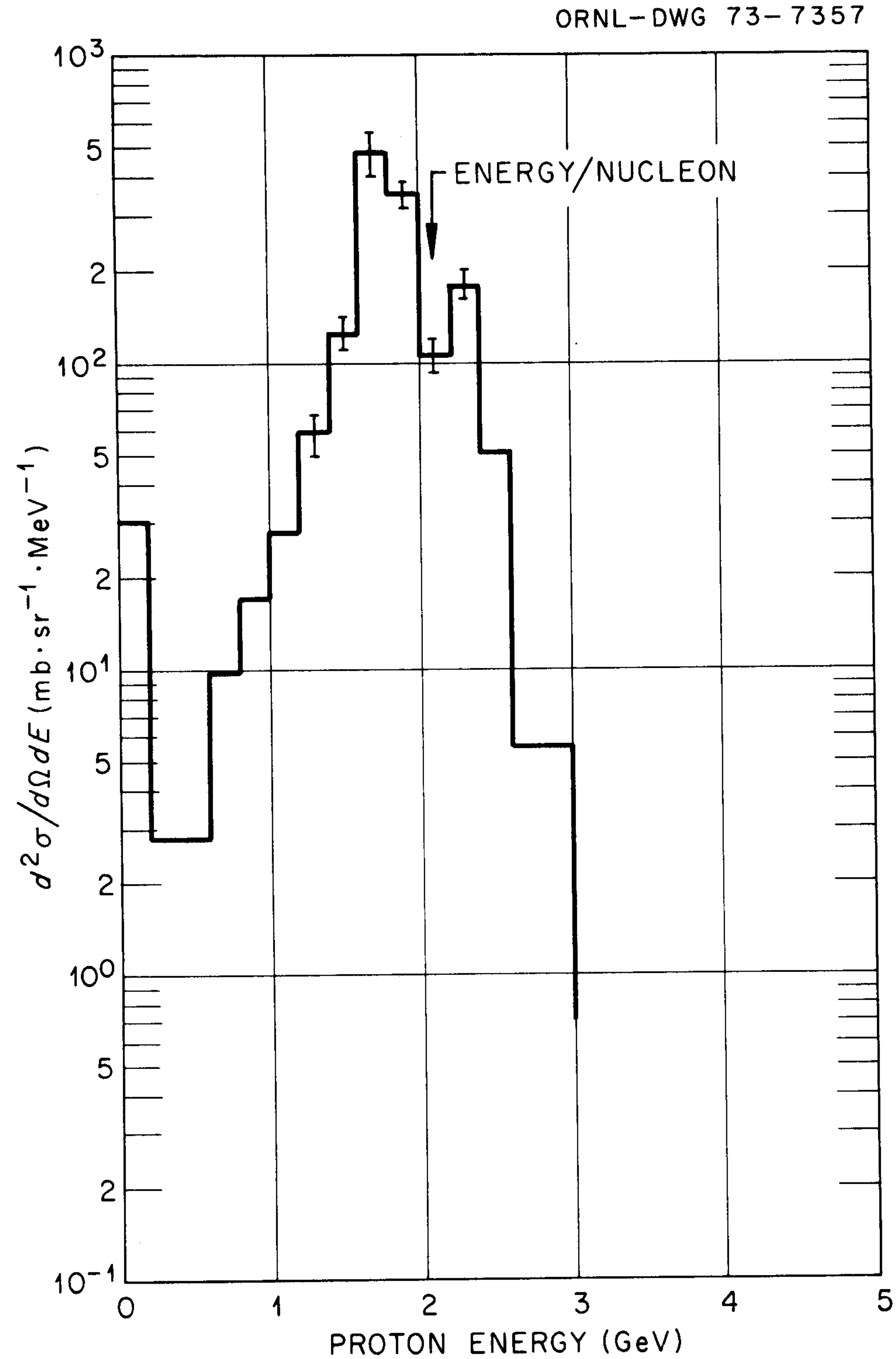


Fig. 1. Proton spectrum for the angular interval 0-10 mrad from 29.4-GeV N on C. The energy per nucleon of the incident projectile is indicated by the arrow.

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