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entitled "Nuclear Reactions Induced by
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INTRODUCTION

This is the final report for the research project entitled "Nuclear Reactions Induced by High-Energy Alpha Particles", supported at the University of Pennsylvania for the period 1 July 1970 to 30 September 1974 by N. A. S. A. research grant NGR-39-010-114.

The principal personnel at the University of Pennsylvania involved in the project were:

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The following is a list of publications and reports made under this project. Aspects of some of these publications were also supported in part by other N.A.S.A. and A.E.C. contracts and grants.

- a. W.J. Nalesnik, T.J. Devlin, M. Merker and B.S.P. Shen,
"Accelerator Measurement of the Spectra of Neutrons Emitted in the Interaction of 3 GeV Protons with Several Elements", Proceedings of the National Symposium on Natural and Manmade Radiation in Space, NASA TMX-2440, 523 (1972).

- b. W. J. Nalesnik, "Energy and Angular Distribution of Neutrons Emitted in the Interactions of 3-GeV Protons with Carbon, Aluminum and Cobalt", Ph. D. Thesis, University of Pennsylvania (1972).
- c. L. Skoski, M. Merker, "Neutron Spectra at 90° from 3 GeV Protons on Carbon, Aluminum and Cobalt", Bulletin of the American Physical Society 18, 692 (1973); abstract.
- d. L. Skoski, "Energy Spectra of Neutrons Emitted in the Interaction of High Energy Protons with Several Elements", Ph. D. Thesis, New York University (1973).
- e. L. Skoski, M. Merker and B.S.P. Shen, "Production Cross-Section of ^{11}C from Carbon Bombarded by High-Energy Heavy Ions", Bulletin of the American Physical Society 17, 489 (1972); abstract.
- f. L. Skoski, M. Merker and B.S.P. Shen, "Absolute Cross-Section for Producing ^{11}C from Carbon by 270 MeV-Per-Nucleon ^{14}N Ions", Physical Review Letters 30, 51 (1973).
- g. E.S. Light, M. Merker, S.A. Korff, and R.B. Mendell, "Solar Modulation of Atmospheric Neutron Flux; Experiment and Calculation", Proceedings of the 12th International Conference on Cosmic Rays 3, 903 (1971).
- h. M. Merker, "Energetic Neutrons Leaking from the Top of the Atmosphere", Physical Review Letters 29, 1531 (1972).
- i. M. Merker, E.S. Light, H.J. Verschell, R.B. Mendell, and S.A. Korff, "The Time-Dependent World-Wide Distribution of Atmospheric Neutrons and of Their Products, 1. Fast Neutron Observations", Journal Geophysical Research 78, 2727 (1973).

- j. E.S. Light, M. Merker, H. J. Verschell, R.B. Mendell, and S.A. Korff, "The Time-Dependent World-Wide Distribution of Atmospheric Neutrons and of their Products, 2. Calculation", *Journal Geophysical Research* 78, 2741 (1973).
- k. R.B. Mendell, H.J. Verschell, M. Merker, E.S. Light, and S.A. Korff, "The Time-Dependent World-Wide Distribution of Atmospheric Neutrons and of Their Products, 3. Neutrons from Solar Protons", *Journal Geophysical Research* 78, 2763 (1973).
- l. M. Merker, "The Contribution of Galactic Cosmic Rays to the Atmospheric Neutron Maximum Dose Equivalent as a Function of Neutron Energy and Altitude", *Health Physics* 25, 524 (1973).
- m. W.F. Schmitt, C.L. Ayres, M. Merker, and B.S.P. Shen, "A Model for Astrophysical Spallation Reactions", *Proceedings of the 13th International Cosmic Ray Conference* 1, 517 (1973).
- n. C.L. Ayres, W.F. Schmitt, M. Merker, and B.S.P. Shen, "Calculation of Astrophysical Spallation Reactions Using the RENO Model", *Proceedings of the 13th International Cosmic Ray Conference* 1, 522 (1973).
- o. C.L. Ayres, Ph. D. Thesis, expected Fall (1974).

DESCRIPTION OF RESEARCH

The original objective of this research was to study experimentally at the Princeton-Pennsylvania Accelerator (PPA) nuclear reactions induced by high energy alpha particles. Due to the early shutdown of the PPA and with the approval of N. A. S. A. , we have included experimental and theoretical studies of nuclear reactions induced by high-energy protons and heavier ions.

The purpose of this research is

- A. to generate fundamental data needed in the shielding, dosimetry, and radiobiology of high-energy particles produced by accelerators,
- B. to generate data needed in the study of the interaction of cosmic rays with matter, e. g. with the earth's atmosphere, and with biological tissue, and
- C. to help elucidate the mechanism of high-energy nucleon-nucleus reactions, especially for light target nuclei of mass number comparable to that of biological tissue.

The research carried out under this grant can be divided into the following three parts:

- I. Experiments at the PPA to study high energy nuclear reactions.
- II. Calculations of the atmospheric nucleonic cascade initiated by the cosmic radiation.
- III. Calculations of the intranuclear cascade and evaporation stages of nuclear reactions induced by high-energy hydrogen, helium and heavier nuclei incident upon light target nuclei, H through Al.

Publications a through f report details and results of the experiments conducted under part I. The experiments were of two types. In one, (publications a through d) neutron spectra produced in the interaction of 3-GeV protons with several elements at several scattering angles were determined by time-of-flight techniques. The results were consistent with the theory of intranuclear cascade and evaporation.

In the other experiments (publications e and f), we measured the production cross-section of ^{11}C in targets of carbon bombarded by 270 MeV/nucleon ^{14}N ions. The data obtained were among the first measured results using high-energy heavy-ions and demonstrated the effects of nuclear interactions between high-energy heavier nuclei.

Publications g through l report our theoretical studies under part II of our research. Atmospheric neutron fluxes and maximum dose equivalents, element production including radiocarbon production rates, and albedo neutron leakage rates were determined by Monte Carlo calculations simulating the interaction of the cosmic radiation with the earth's atmosphere. The results, which show close agreement with experimental measurements where available, confirm the usefulness of this theoretical technique in difficult transport calculations as well as determine important data of the nucleonic cascade in the atmosphere.

Publications m through o describe our research under part III, intended to study nuclear interactions among the lighter elements hydrogen through aluminum using the RENO (Random Encounters between Nuclear Objects) model. The RENO model simulates the intranuclear cascade and

evaporation stages of nuclear reactions by Monte Carlo techniques. The original RENO model, a computer program developed principally by W. F. Schmitt of our group and described in his dissertation ("A Monte Carlo Calculation of Spallation Reactions of Astrophysical Interest in the M Nuclei", Ph. D. Thesis, University of Pennsylvania (1970)), has been modified to accommodate interactions at higher energies and between heavier elements. A description of the modifications to the model follows:

The work has consisted of the development of an intranuclear cascade simulation program capable of predicting the results of collisions between light and medium nuclei at high energies. Although a number of programs are available for the simulation of cascades produced by free nucleons incident on nuclei, there have been few attempts to model collisions between complex nuclei.

The model used in the program is based on that of Schmitt, which represents nuclei as clusters of discrete point nucleons, instead of the usual Fermi-sea probability distribution, an approach which greatly simplifies the modeling of nucleus-nucleus interactions. However, a number of improvements and extensions have been made over the original model. These include:

a) Generalization of the initial state.

Schmitt's original program has been rewritten and expanded from a version which permitted only incident protons and alphas to one which permits any light nucleus or pion as either the incident or the target particle.

b) Exact dynamics.

A number of dynamical approximations used by Schmitt have been replaced by exact calculations. This becomes increasingly necessary as higher energy collisions are considered, and the relativistic effects become more pronounced. In addition, the nuclei are given their known atomic masses in the calculations, rather than integral multiples of the proton mass as in the earlier version.

c) Inclusion of pions.

The production of pions during collisions and their subsequent interactions with other nucleons in the cascade have been included in the model. This permits the simulation of collisions at higher energies than before; it also makes possible cascades produced by incident pions. The pion-production is based on the Sternheimer-Lindenbaum model, in which the pions are produced via an intermediate heavy-hyperon state of the nucleon or nucleons in the collision. The hyperon has a variable mass, dependent on the energy available in the collision - it then decays by the emission of a pion. By this algorithm, up to two pions can be produced at each nucleon-nucleon encounter, one at each pion-nucleon encounter, provided the energy is sufficient. Empirical elastic and inelastic nucleon-nucleon and pion-nucleon cross-sections and differential cross-sections are used to model the individual interactions within a cascade.

d) Reformulation of the reaction-selection algorithm.

In the Schmitt model, selection of the mode of breakup resulting

from a nucleon-nucleon collision was governed by an ad hoc probability equation of the form:

$$P_n = \frac{1}{\alpha_n (E - E_n)^{\gamma_n} + \beta};$$

this being designed to resemble a resonance pattern around energy E_n .

In the new version, a similar algorithm is used, but the probability expression has an additional term which will dominate at high energies. It now reads:

$$P_n = \frac{1}{\alpha_n (E - E_n)^2 + \beta} + \gamma_n E.$$

The coefficients α_n and γ_n are chosen by trial and error to give the best results when compared with experiment. They may be entered by the user as input if desired.

e) Generation of history file:

The program now generates a file on tape or disk as well as a printed output. The secondary file contains the initial and final states of all interacting cascades; it may be used as input to a second program in order to generate additional statistics about the run without repeating the simulation.

A series of runs is currently under way to obtain an optimal set of the reaction-selection coefficients mentioned in paragraph (d) above.

The program in its present form will simulate bombardments in which the incident and target particles may be pions, free nucleons, or any

light or medium nucleus, provided only that the sum of nucleons in incident and target particles does not exceed 32. It will accommodate energies from a minimum of 20 MeV per nucleon (or per pion) up into the GeV range; however, the model does not take into account nucleon-antinucleon pair production or triple-pion production, which puts an upper limit on the incident energies at which it can be useful. It provides total elastic and inelastic cross-sections, nuclide production cross-sections, and outgoing spectra for pions and free nucleons. In conjunction with the secondary program which reads the output tape, it can also provide outgoing spectra for any species of nucleus.

A detailed description of the modifications to the Schmitt model and calculations using the model will be presented in publication of the dissertation of C. L. Ayres, which is expected to be completed this fall and will be forwarded. In addition, we are providing our N. A. S. A. technical officer, at his request, with a tape of RENO and auxiliary programs, as well as a user's guide and a sample calculation.