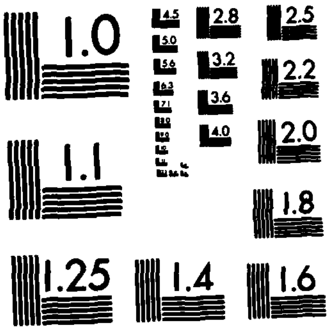
AD-A123 111 THEORETICAL INVESTIGATION OF THICK-TARGET NUCLEAR SIGNATURES(U) SCIENCE APPLICATIONS INC LA JOLLA CA T W ARMSTRONG ET AL. AUG 82 SAI-134-82-225-LJ 1/1

UNCLASSIFIED AFOSR-TR-82-1068 F49620-81-C-0044 F/G 18/8 NL

END

FILMED

DTIC



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

AFOSR-TR- 82-1068

12

# SCIENCE APPLICATIONS, INC.

SAI-134-82-225-LJ

12

# THEORETICAL INVESTIGATION
# OF
# THICK-TARGET NUCLEAR SIGNATURES

DTIC
ELECTE
JAN 7 1983
H

By

T.W. Armstrong
B.L. Colborn

August 1982

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH (AFSC)
NOTICE OF TRANSMITTAL TO DTIC
This technical report has been reviewed and is
approved for public release IAW AFR 190-12.
Distribution is unlimited.
MATTHEW J. KERPER
Chief, Technical Information Division

Research sponsored by the Air Force Office
of Scientific Research (AFWC) under Contract
F49620-81-C-0044, Amendment P00001.

SCIENCE APPLICATIONS, LA JOLLA, CALIFORNIA
ALBUQUERQUE • ANN ARBOR • ARLINGTON • ATLANTA • BOSTON • CHICAGO • HUNTSVILLE
LOS ANGELES • McLEAN • PALO ALTO • SANTA BARBARA • SUNNYVALE • TUCSON

P.O. Box 2351, 1200 Prospect Street, La Jolla, California 92037

UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

## REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS
BEFORE COMPLETING FORM

| | | |
|---|---|---|
| 1. REPORT NUMBER<br>AFOSR-TR- 82-1068<br>[redacted] | 2. GOVT ACCESSION NO.<br>AD-A123111 | 3. RECIPIENT'S CATALOG NUMBER |

4. TITLE (and Subtitle)
THEORETICAL INVESTIGATION OF THICK-TARGET NUCLEAR SIGNATURES

5. TYPE OF REPORT & PERIOD COVERED
Final, 5/81 - 4/82

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s)
T.W. Armstrong and B.L. Colborn

8. CONTRACT OR GRANT NUMBER(s)
F49620-81-C-0044
[redacted]

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Science Applications, Inc.
1200 Prospect Str., P.O. Box 2351
La Jolla, CA 92038

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
61102F
Project No. 2301/A7

11. CONTROLLING OFFICE NAME AND ADDRESS
Air Force Office of Scientific Research
Attn: NP, Building 410
Bolling AFB, DC 20332

12. REPORT DATE
August 1982

13. NUMBER OF PAGES
15

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)

15. SECURITY CLASS. (of this report)
Unclassified

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release;
distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Neutron Yields, Gamma-Ray Yields, Heavy Ions, Spallation Reactions, Monte Carlo Methods

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This study concerns the development of nuclear spallation models to allow the prediction of γ-rays and neutrons emitted in the backward directions from thick targets of various material compositions when bombarded by various types of ions (hydrogen through lithium) in the energy range from about 50 MeV to several hundred MeV. A theoretical high-energy nuclear interaction model (the intranuclear-cascade-evaporation model) is extended to treat secondary particle production from ion beam collisions, and this model is incorporated in thick-target radiation transport computer codes. Monte Carlo methods are used in computing

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

Item 20. continued

both the nuclear interaction products and the radiation transport. Example results from applying these models are given for various ions bombarding an aluminum target.

# TABLE OF CONTENTS

Appendix

# 1. Introduction

This report constitutes the final report on work performed under Air Force Office of Scientific Research Contract No. F49620-81-C-0004 (Amendment P00001), Project No. 2301/A7 entitled "Theoretical Investigation of Thick-Target Nuclear Signatures".

The subject of the study concerns predictions of $\gamma$-rays and neutrons emitted in the backward directions from thick-targets of various material compositions when bombarded by various types of ions (hydrogen through lithium) in the energy range from about 50 MeV to several hundred MeV.

The original scope of the study consisted of the following tasks:

1. extend the capabilities of previous nuclear interaction models and radiation transport computer codes to treat essentially arbitrary target composition and to allow heavier ion beam masses (through lithium ions),
2. carry out calculations of the "backscattered" neutron and $\gamma$-ray spectra for specific cases for which experiments (under a separate program) were to be performed,
3. perform systematic theoretical/experimental comparisons of yields and spectra to access the accuracy of the models and calculational methods, and
4. assess the detectability of the $\gamma$- and neutron-radiation, including background radiation effects.

(The detailed statement-of-work for the original study is included here in the appendix.)

Due to unforeseen circumstances, the planned associated experimental program was not carried out, so the performance of Tasks 2-4 above were not possible. Thus, only part of Task 1 above was carried out under the present study. This work consisted of initial nuclear model modifications and extensions to include fast-fission reactions for uranium targets, as described in Section 2.

Subsequent to this study, under separate support from the Air Force Weapons Laboratory (AFWL), work under Task 1 was completed, the computer codes were made operable on computers at the AFWL, and calculations were carried out for several beam parameters. A few of these results are included here as Section 3 to indicate that the predicted $\gamma$ and neutron yields and spectra appear to be reasonable qualitatively, but to date there has not been experimental verification.

## 2. Nuclear Model Extensions

The basic method employed for calculating the neutron and $\gamma$-ray yields from high-energy ion bombardment of thick targets is to use theoretical nuclear interaction models and thick target radiation transport computer codes. Monte Carlo methods are used in computing both the nuclear interaction products and the radiation transport.

The work here is an extension of previous methods that have been developed for lower-mass ions, as summarized in Section 2.1 below. Modifications made in this study to allow incident ions up to lithium are described in Section 2.2, and modifications to incorporate fast fission reactions to allow predictions for uranium targets are described in Section 2.3.

### 2.1 Background

Consider an energetic ion beam having a kinetic energy of, say, a few hundred MeV and low-mass (in the range from $^1H$ to $^7Li$) bombarding a target where the target thickness is $\gtrsim$ the ion range. The main physical processes to be simulated are as follows:

1. Inside the target, the primary beam loses energy by atomic processes (ionization and excitation) and undergoes nuclear interactions ("spallation" collisions).
2. These spallation reactions produce: (a) high-energy neutrons and protons (up to the energy/nucleon of the ion), which travel to produce additional spallation reactions, inducing a "hadron cascade" inside the target material, (b) low-energy particles (deuterons, tritons, etc.) which have very short ranges, and are not of interest here, and (c) "spallation" $\gamma$-rays from nuclear de-excitation.
3. The low-energy neutrons ($\lesssim$ 15 MeV) produced can also undergo inelastic scattering $(n, n'\gamma)$ and capture $(n,\gamma)$ reactions to produce an additional source of $\gamma$-rays.

The main concern here is to simulate in detail these interaction and transport processes to determine the energy spectrum of those neutrons and $\gamma$-rays which escape from the beam-entrance face of the target.

## Nuclear Models

We divide nuclear collisions into two categories: (a) spallation collisions, which we take to be collisions induced by all particles (neutrons, protons, and primary ions) having energies $\gtrsim$ 20 MeV per nucleon, and (b) low-energy ($\lesssim$ 20 MeV) neutron collisions. The reason for this division is that experimental data are available for treating low-energy neutron reactions (from extensive research related to nuclear reactors), so we can utilize the rather extensive experimentally derived cross section libraries in this energy range. For the spallation reactions, adequate experimental data are not available, so we resort a theoretical model, as described below. For charged particles below $\sim$ 20 MeV/nucleon, it is assumed that the particles stop and come to rest before undergoing nuclear collision.

The intranuclear-cascade-evaporation (ICE) model has been applied successfully for some years for treating spallation reactions induced by nucleons and charged pions (e.g., Ref. 1 ). This model assumes that the reaction takes place in two phases. In the first phase (intranuclear cascade step) the collisions which take place inside the nucleus between the incident particle the individual neutrons and protons inside the nucleus are computed using Monte Carlo methods, taking into account the Fermi motion of the nucleons and forbidden collisions due to the Pauli principle. An important advantage of this model is that the principal input data required are particle-particle cross sections (nucleon-nucleon and pion-nucleon) which are rather well known experimentally. The residual excitation energy after the intranuclear cascade is assumed to be uniformly distributed, and a statistical ("evaporation") model is then applied as a second step to determine further particle emission via de-excitation. This model has also been applied to treat heavier incident particles (deuterons through alpha particles), Ref. 2, and was extended in this study to treat projectile ions through lithium (Section 2.2).

The "standard" ICE model assumes that the residual excitation energy left after particle emission is no longer energetically possible by evaporation is dissipated by $\gamma$-ray emission, but the $\gamma$-ray spectrum is not determined. Extensions of the model have been made previously to determine the energy spectrum of these spallation $\gamma$-rays by computing the transition probabilities and energies between energy levels during de-excitation (Ref. 3 ).

## Radiation Transport

For the transport of the incident ions and high-energy nucleons, a modified version of the Monte Carlo radiation transport code HETC (Ref. 4 ) is used. This code incorporates the ICE spallation model, and computes the trajectories and collisions for all secondary particle production.

The high-energy transport code also computes the low-energy neutrons produced in spallation collisions. The energy, direction, and spatial point of each low-energy neutron ($\lesssim$ 20 MeV) produced in spallation collisions during the high-energy radiation transport is written on an output tape. This tape is then used as an input neutron source to the low-energy transport code MORSE (Ref. 5 ). The MORSE code is then used to perform a coupled neutron/$\gamma$-ray transport calculation - i.e., the $\gamma$-rays produced by low-energy neutron interactions are also transported. The nuclear interaction cross sections needed for the MORSE calculations can be taken from several available compilations which are maintained and routinely updated with newly measured data, such as the Evaluated Nuclear Data File (Ref. 6).

The high-energy transport calculation also provides the residual excitation energy and type of nucleus (charge and mass numbers) left after spallation reactions. This information for each collision is used to compute, in a separate computer program, the spectrum of $\gamma$-rays produced. These spallation $\gamma$-rays are then used as a source for the MORSE code to determine the transport of these $\gamma$-rays throughout the target.

Both the high-energy and low-energy transport codes are general purpose, providing a "record" of all essentially events which take place during the Monte Carlo simulation. Analysis programs of these recorded histories are then written to extract the relevant information for a particular problem of interest. For present interests, the analysis programs are written to compute the spectra (and integral) of neutrons and $\gamma$-rays escaping the target through the beam-entrance surface.

A summary of the calculational steps involved is given in Figure 1.

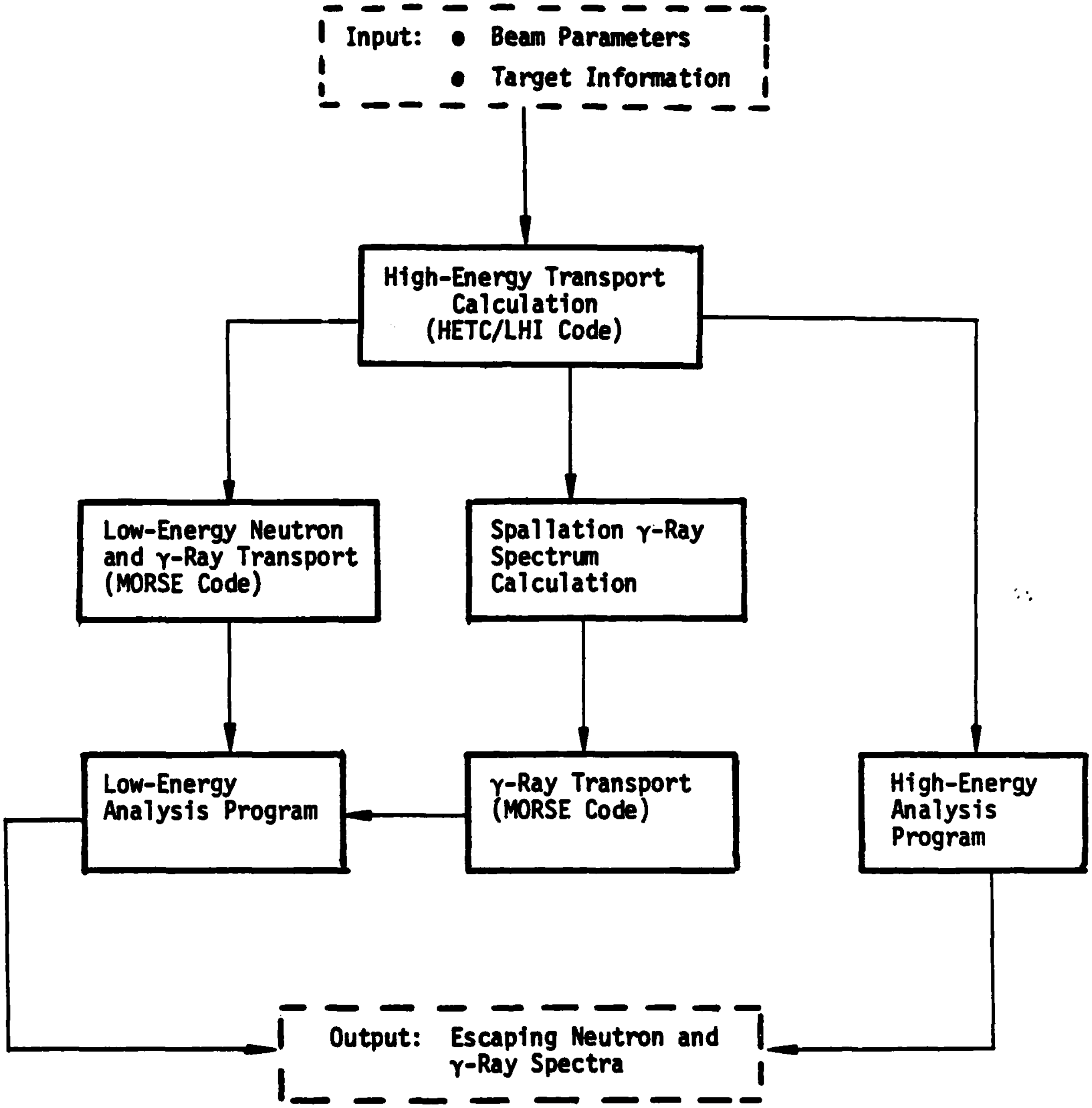


Figure 1. Calculational Method For Radiation Transport

## 2.2 Intranuclear-Casecade-Evaporation Model Modifications For Ion-Nucleus Collisions

In extending the ICE model to predict the products from reactions induced by projectiles of $A > 1$, the basic assumption is made that the projectile can be considered as a cluster of independent nucleons. The reaction is then computed, in effect, as the sum of the effects of these independent nucleons striking the nucleus. This approximation would appear to be quite valid for ions only slightly higher than nucleons. However, this approximation is expected to become progressively worse as the projectile ion mass increases, where cascade reactions can be induced in the projectile particle as well as the target nucleus. In the present work we have made modifications to the ICE model using the independent nucleon approach to allow projectiles up to $A = 10$, although the heaviest ion for which complete calculations have been made to date using the method outlined in Figure 1 has been for $^{7}$Li.

To determine the collision site and the type of struck nucleus in the target material composition, an empirical formula for the nonelastic nuclear cross section is used: $\sigma = \pi(R_i + R_T - \delta)^2$, where $R_T = r_0 A_T^{1/3}$ is the radius of the target nucleus, $R_i = 2.19\ A_i^{1/3} \times 10^{-13}$ cm is the ion radius, $r_0 = 1.42 \times 10^{-13}$ cm, and $\delta = 0.80 \times 10^{-13}$ cm.

Next, the impact parameter of the center-of-mass of the ion is determined by selecting a point, with uniform probability, over a projected circular area of radius $R_i + R_T$. To determine the spatial coordinates at which each nucleon of the projectile strikes the target nucleus, a configuration for the cluster relative to the projectile conter-of-mass must be assumed. We assume that one-half of the nucleons are located at each end of a line a distance $R_i$ from the projectile center of mass, with probability of 0.5 that the additional nucleon for odd $A_i$ is located at either end. The projectile cluster is allowed to have a uniform azimuthal orientation. Thus, this procedure defines the position on the surface of the target nucleus which each nucleon of the projectile enters. The kinetic energy of each nucleon as it enters the nucleus is taken to be $(E - E_B)/A_i$, where $E$ and $E_B$ are the kinetic and binding energies of the ion.

An intranuclear cascade calculation is then performed for each projectile nucleon, and the sum of the produced secondary particles represents the cascade products for the ion interaction. The A, Z, and E* (excitation energy) after the cascade phase is then used as input for an evaporation calculation in the same manner as in the standard model for nucleon-nucleus collisions.

For targets containing hydrogen, ion collisions with proton nuclei are treated using the same nucleon-nucleon cross sections as are used in the intranuclear cascade portion of the calculation together with the algorithm given in Ref. 2. The projectile ion energy loss by atomic ionization and excitation is determined by scaling the stopping values for protons, as described in Ref. 2.

## 2.3 Fast Fission Mechanism

For particle interactions with very heavy target nuclei (e.g., uranium), the two-step intranuclear cascade plus evaporation model discussed above should, according to experimental evidence, be modified to take into account an additional de-excitation mechanism: "fast" fission. That is, after the intranuclear cascade step, there is "competition" at each stage of de-excitation (i.e., after each particle emission) as to whether the residual nucleus continues to evaporate particles from a single fragment or whether the residual nucleus fissions into two fragments, with each fission fragment continuing de-excitation by evaporating particles. The overall emitted particle multiplicities and spectra from the interaction are expected to be somewhat different if fission takes place.

The probability that fission will occur given a nonelastic interaction depends upon the particle type, particle energy, and target nucleus. For example, for protons of $\sim$ 100 MeV, the fission probability is $\approx$ 0.8 for $U^{238}$, $\approx$ 0.5 for $Th^{232}$, and $\approx$ 0.05 for $Bi^{209}$, with the fission probability varying roughly as $Z^2/A$ of the target nucleus (Ref. 7). Thus, for present interests high-energy fission is most important only for target compositions containing uranium. In general, the probability of fission increases with particle mass and energy.

In order to provide the computational capability of predicting escaping neutrons and gamma-rays from thick targets containing uranium, the ICE model was modified to incorporate the fast fission mechanism. The basic procedure and assumptions follow those of References 8 - 10, and the major steps are summarized below.

The main items to be specified are the probability of fission at each step of de-excitation and a description of the fission fragments (i.e., kinetic energy, excitation energy, Z, and A) if fission takes place. The fission probability is written as

$$P_f = (1 - \Gamma_n/\Gamma_f)^{-1}$$

where $\Gamma_n$ and $\Gamma_f$ are the widths for neutron emission by evaporation and for fission, respectively. In the actinide region ($Z > 90$), the empirical formula of Vandenbosh and Huizenga (Ref. 11) is used,

$$\log \frac{\Gamma_n}{\Gamma_f} = \Phi(Z)A + \phi(Z),$$

where the coefficients $\Phi$ and $\phi$ are based on systematics and have been tabulated in Ref. 12 . $P_f$ is assumed to be independent of excitation energy $E^*$ for $E^* > 6$ MeV, and $P_f = 0$ for $E^* < 6$ MeV. For residual nuclei in the subactivite region ($Z \leqslant 90$), statistical model fits to experimental data are used:

$$\Gamma_n = 0.352[1.68I_0 + 1.93A^{1/3}I_1 + A^{2/3}(0.76I_1 - 0.05I_0)]$$

$$I_0 = \frac{4.0}{a_n}[(S_n - 1.0)\,e^{S_n} + 1]$$

$$I_1 = \frac{2.0}{a_n^2}[(6.0 - 6.0S_n + 2.0S_n^2)\,e^{S_n} + S_n^2 - 6.0]$$

$$S_n = 2.0\,[(a_n\,(E^* - B)]^{1/2}$$

$B$ = separation energy minus paring energy

$$a_n = (A - 1.0)/8$$

$$\Gamma_f = [(S_f - 1.0)\,e^{S_f} + 1.0]/a_f$$

$$S_f = 2.0[a_f(E^* - E_f)]^{1/2}$$

$$E_f = B - 321.2 - 16.7(Z^2/A) + 0.219(Z^2/A)^2$$

$$a_f/a_n = 1.09 + 0.011(Z^2/A - 31.1)^2.$$

The basic equations above are based on the statistical model (e.g., Ref. 13). The parameters which have been fit to experimental data are the fission barrier $E_f$ and $a_f/a_n$ (ratio of level density parameter for fission to level density parameter for neutron emission).

The kinetic energy of the fission fragments arises from mutual coulomb repulsion, so the sum of fragment energies $E_k$ is expected to correlate with the coulomb repulsion parameter $Z^2/A^{1/3}$. From the fits to experimental data made in Ref. 14 ,

$$E_k(\text{MeV}) = 0.1065(Z^2/A^{1/3}) + 20.1$$

The recoil energy for each fragment is then given by the relations $E_{k_1} = [A_2/(A_1 + A_2)]\ E_k$ and $E_{k_2} = [A_1/(A_1 + A_2)]\ E_k$. The excitation energy of the fragments is then determined by energy conservation - i.e.,

$$E_T = M(A,Z) + E^* - M(A_1,Z_1) - M(A_2,Z_2)$$

where M denotes nuclear mass and E* is the excitation energy of the fissioning nucleus. The fragment excitation energies then are

$$E_1^* = [A_1/(A_1 + A_2)]\ (E_T - E_k) \text{ and}$$

$$E_2^* = [A_2/(A_1 + A_2)]\ (E_T - E_k).$$

The most appropriate method for specifying fragment masses is not clear, either from theory or measurements. The shape of fission mass distribution can be either symmetric (one peak) or asymmetric (two peaks), depending on the fissioning nucleus and its excitation energy (e.g., Ref. 7 ). In the actinide region the data of Ref. 14 is utilized, which shows that the mean mass of the heavy fragment is essentially constant at about 140 independent of the fission nucleus mass, $A_F$ (for $A_F \approx 225$ to $\approx 255$), and the light fragment mass increases linearly from about 90 to 120 as $A_F$ increases. In the subactinide region, the mean mass of each fragment is about $A_F/2$, with a normal distribution having a half-width-at-half-maximum, <W>, of (Ref. 15): $\langle W\rangle = E^* - E_f - 7$ (a.m.u.).

The procedure for treating high-energy fission reactions then is as follows: First, the intranuclear cascade phase of the calculation is performed in the usual manner (i.e., this "fast" part of the interaction is the same whether fission takes place or not). The residual nucleus A,Z, and E* is then used with the probability of fission $P_f$ defined above to "select" (in a Monte Carlo sense) whether the nucleus at this stage de-excites by undergoing fission or evaporation. If fission is selected, a description of the fragments is determined using the methods described above, and evaporation calculations are performed for each fragment to compute particle emissions during complete fragment de-excitation. If evaporation was selected, an evaporation calculation for the cascade residual nucleus is performed for a single particle emission, and the probability of fission is then tested again. Thus, the evaporation-fission competition is applied at each step of de-excitation - i.e., after each evaporated particle.

The fast-fission reaction mechanism as described above has been programmed in the HETC/LHI code, but is largely untested at this time. (Low-energy fission reactions, due to neutrons below ≈ 20 MeV produced in high-energy collisions, can be taken into account as one of the standard options of the MORSE transport code.)

## 3. Results From Transport Calculations

While not part of the present study, the nuclear model development described in Section 2 has been applied for one case under an AFWL sponsored study (Ref. 16), and a few of these results are included here to illustrate applications of the models.

The case considered was $Li^7$ ions of 380 and 840 MeV incident on a thick aluminum target. (These energies correspond to ranges in aluminum of about 3 and 10 g/cm$^2$.) Radiation transport calculations were carried out using the code system shown previously in Figure 1. The spectra of neutrons and gamma-rays escaping the target in the backward hemisphere are shown in Figure 2. The "backscattered" gamma-ray and neutron yields for Li ions are compared in Figures 3 and 4 with results for other ions.

Thus, the Li interaction model appears to work properly based on systematics, but there are no measured data available for quantitative evaluation.

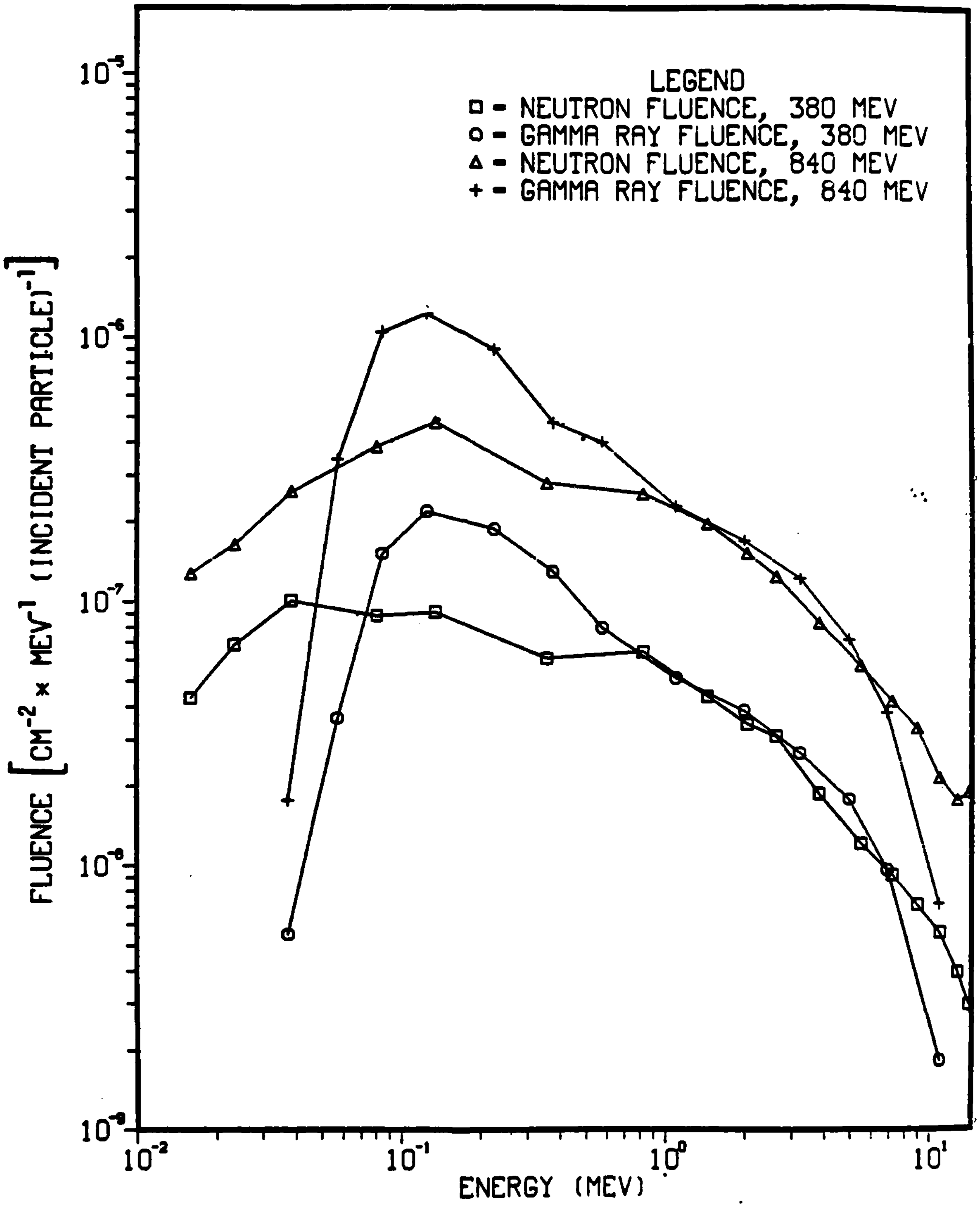


Figure 2. Neutron and gamma-ray spectra emitted over all backward directions for 340 and 840 MeV Li beams incident on an aluminum target (from Ref. 16).

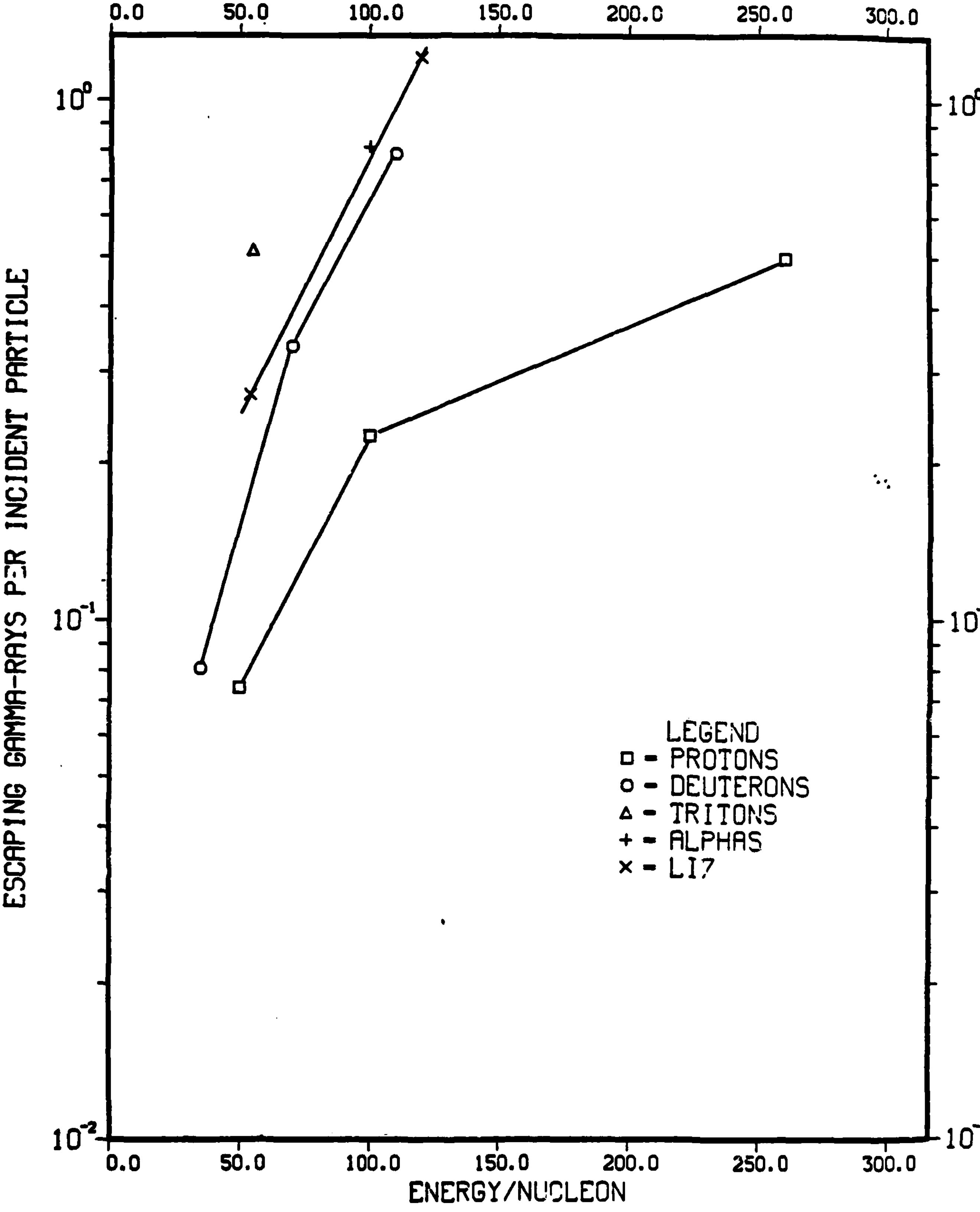


Figure 3. Dependence of the number of "backscattered" gamma rays on ion energy (from Ref. 16).

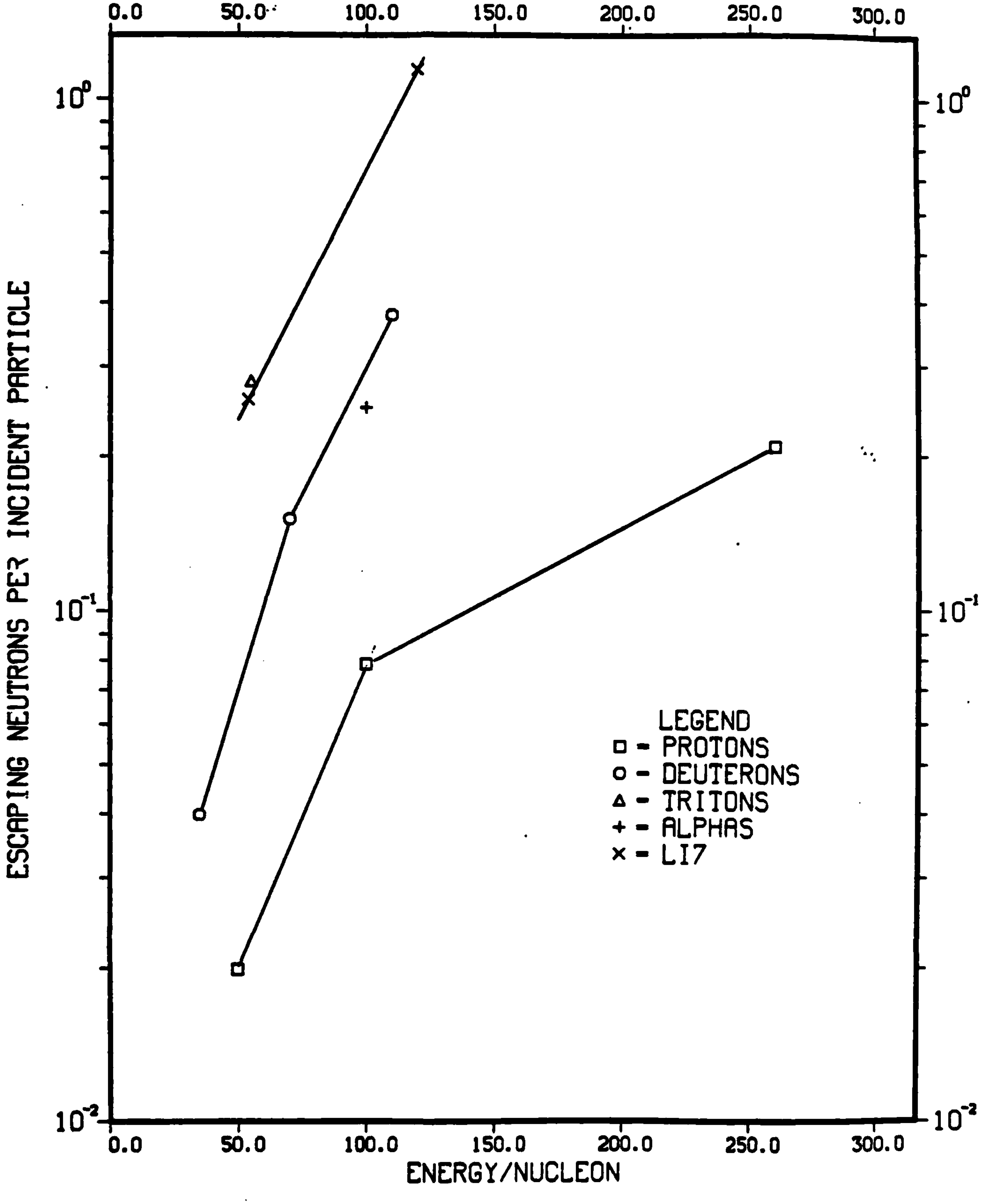


Figure 4. Like Figure 3 but for Neutrons (from Ref. 16).

# REFERENCES

1. T.W. Armstrong, "The Intranuclear-Cascade-Evaporation Model", Chapter 20 in Computer Techniques in Radiation Transport and Dosimetry, Walter R. Nelson and Theodore M. Jenkins (Eds.), Plenum Press, New York, 1980.

2. T.W. Armstrong and B.L. Colborn, "A Thick-Target Radiation Transport Computer Code for Low-Mass Heavy Ion Beams", Nucl. Instr. Meth. 169, 161 (1980).

3. M. Merker, B. Colborn, and T. Armstrong, "Theoretical Predictions of Return Signals", SAI-134-79-973-LJ, December 1979.

4. T.W. Armstrong and K.C. Chandler, "HETC - A High Energy Transport Code", Nucl. Sci. and Engr. 49, 110 (1972).

5. E.A. Straker, W.H. Scott, and N.R. Byrn, "The MORSE Code with Combinatorial Geometry", SAI-72-511-LJ, 1972.

6. D. Garber, C. Dunford, and S. Pearlstein, "Data Formats and Procedures for the Evaluated Nuclear Data File, ENDF", BNL-NCS-50496 (ENDF 102), October 1975.

7. E.K. Hyde, The Nuclear Properties of Heavy Elements, Vol. III: Fission Phenomena, Prentice-Hall, Inc., Englewood Cliffs, N.J. (1964).

8. V.S. Barashenkov, V.M. Mal'tsev, and V.D. Toneev, "Calculation of Fast Particle Induced Fission", JINR-P-1978, Dubna, U.S.S.R. (1965).

9. V.S. Barashenkov and V.D. Toneev, "Neutron Fluxes Generated by High-Energy Protons on Thick Blocks of Uranium", Atomnaya Energiza 35, 163 (1973).

10. F. Atchinson, Rutherford-Appleton Laboratory, U.K., private communication, 1981.

11. R. Vandenbosh and J.R. Huizanga, Nuclear Fission, Academic Press (1973).

12. A. Gavron, et al., "$\Gamma_n/\Gamma_f$ for Actinide Nuclei using ($^3$He,df) and ($^3$He,tf) Reactions", Phys. Rev. C13, 2374 (1976).

13. J.M. Blatt and V.F. Weisskopf, Theoretical Nuclear Physics, John Wiley & Sons, 1952.

14. J.P. Unik, et al. "Fragment Mass and Kinetic Energy Distribution for Fission Systems Ranging from Mass 230 to 256", Proc. of 3rd Symposium on the Physics and Chemistry of Fission, Rochester, NY (1979).

15. E.F. Neuzil and A.W. Fairhall, Fission Product Yields in Helium Ion Induced Fission of Au-197, Pb-204, and Pb-206 Targets", Phys. Rev. 129, 2705 (1963).

16. T.W. Armstrong and B.L. Colborn, "Nuclear Model Development and Applications For High-Energy Lithium Ion Bombardment of Thick Targets", SAI-134-81-375-LJ, October 1981.

# APPENDIX

## Statement-of-Work for Original Contract

## PART I - THE SCHEDULE

## SECTION B - SUPPLIES/SERVICES AND PRICES

0001 RESEARCH

The contractor shall furnish the level of effort specified in Section F, together with all related services, facilities, supplies and materials needed to conduct the research described below. The research shall be conducted during the period specified in Section F.

0001AA

a. The contractor will exercise his best efforts to perform a theoretical investigation of the nuclear return signature of thick targets bombarded by energetic light nuclei. The study will generally include both calculational and assessment tasks. Specific tasks to be accomplished will include the following:

(1) Implement modifications and improvements in the HETC/LHI code system required to efficiently perform parametric yield predictions for a range of light beam ions, energies, and targets, and shall deliver an operating version of the modified HETC/LHI code system source listing to AFWL/NTYP.

(2) Perform a series of specific calculations of neutron and gamma ray thick-target yields. Representative light, intermediate, and heavy target nuclei will be considered, and beam particles of several masses between $H^1$ and $Li^6$ will be included. Energies of the incident beam ions will be chosen to provide coverage consistent with penetration depths similar to the proton energy region 50-200 MeV. Specific energies needed for validation by comparison with experiment will be included.

(3) Organize and interpret the calculational results. Comparisons with available experimental data will be made, and interpretation of possible discrepancies and uncertainties will be made in terms of their significance to model validation.

(4) Carry out a preliminary detectability assessment, with the theoretical results as a basis. Background sources will be identified and quantified. Results of the detectability assessment will include comparisons with estimated X-ray yields and backgrounds.

(5) Document the results of the study as appropriate. Fundamental results will be made available to the technical community through the open technical literature.