Conf 921041--9

BNL--48035

DE93 003167

# METHODS USED TO PRODUCE NUCLEAR DATA FILES FOR 0 - 10 GEV INCIDENT NEUTRONS AND PROTONS*

Received OSTI

NOV 2 0 1992

SOL PEARLSTEIN

*Department of Nuclear Energy, Brookhaven National Laboratory*
*Upton, New York 11973, U.S.A.*

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

ABSTRACT

Nuclear models for calculating medium energy data are in need of a unified theory. For energies above 100 MeV the incident nucleon wavelength is smaller than its collision mean-free-path within the target nucleus so that an intra-nuclear-cascade model, for example, is appropriate. For energies below 100 MeV the incident nucleon wavelength is larger than the dimensions of the target nucleus so that a partial wave nuclear model, for example, is appropriate. Comparisons between calculations and experiments show discrepancies even when using appropriate models. Experimental data alone is rarely convergent or sufficient to define an evaluation over the complete range of interest. The evaluator is therefore left to selectively choose from a diverse arsenal of experimental data, nuclear models and nuclear systematics those tools that may best help him to complete an evaluation. These points are illustrated by the use of calculation and experiment in the evaluation of nucleon data for $^{12}C$.

## 1. Introduction

### *1.1. Evaluation Tools*

There is an overlap of the nuclear data requirements for applications that include space exploration, astrophysics, accelerator shield design, spallation neutron sources, radiation therapy and medical isotope production. The total energy range of interest is 0 - 10 GeV. There is no one nuclear theory or model code validated over this energy range. For energies above 100 MeV the incident nucleon wavelength is smaller than its collision mean-free-path within the target nucleus so that an intra-nuclear-cascade model, for example, is appropriate. For energies below 100 MeV the incident nucleon wavelength is larger than the dimensions of the target nucleus so that a partial wave nuclear model, for example, is appropriate. These characteristics can be seen by looking at the total cross section for neutrons on Pb as shown in Fig. 1. Below about 200 MeV the total cross section is oscillatory mainly due to the Ramsauer effect of interference between the incident neutron wave traversing the target nucleus and the neutron wave going around. Above 200 MeV the total cross section is relatively flat as expected for nucleon-nucleon collisions.

In the case of the well measured total cross section for neutrons on Pb even the most indecisive evaluators could agree on an evaluated cross section but the experimental data alone is rarely convergent or sufficient to define an evaluation over the complete phase space of interest. Some nuclear model codes are a marvel in the sense that they provide answers to all of the questions asked by the evaluator. To determine if the answers are correct comparisons between calculations and

*This work was performed under the auspicies of the U.S. Department of Energy.

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

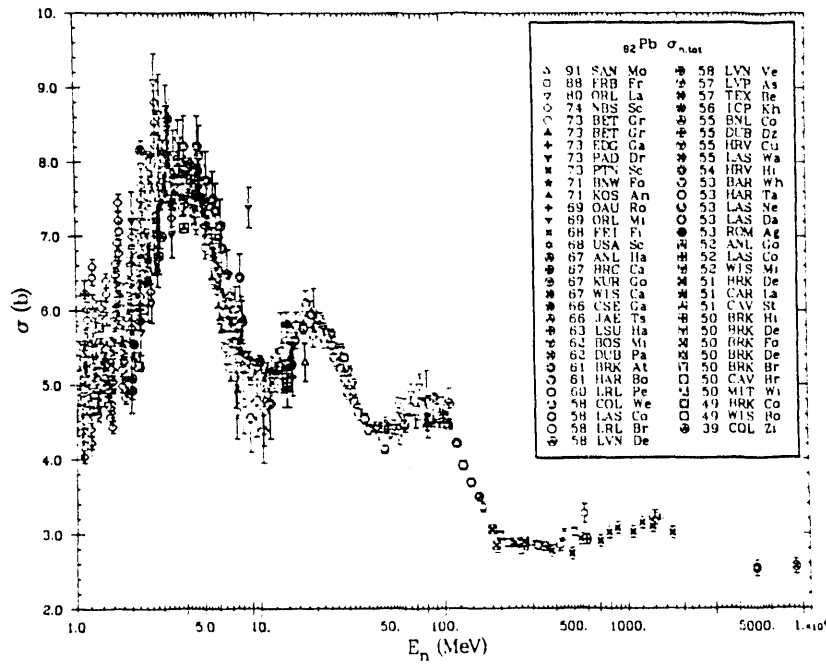


Figure 1: Total cross section for neutrons on lead.

experiments are made when possible. This approach is not fool proof because some experiments can systematically be wrong in both magnitude and shape.

The evaluator is therefore left to cautiously choose those methods that may best help him to complete an evaluation. They are the following:

1. Experimental data bases. Data contained in this article or references to such data are typical of that obtainable from the National Nuclear Data Center[1].

2. Nuclear model codes. There are many codes useful to evaluators of medium energy data. Some information about medium energy codes have been collected[2,3,4].

3. Nuclear systematics. These are semi-empirical formulas that can be useful in estimating data where measurements have not been made. Formulas based on medium energy systematics are readily available[4,5].

4. Arithmetic strategies. Statistical averaging, spline fitting and smoothing, interpolation, extrapolation, etc., may be useful to filling gaps and arriving at recommended values for the cross section.

### *1.2. Evaluated Data for $^{12}C$*

As an example of the methods used to produce data files for 0 - 10 GeV incident neutrons and protons the data for a $^{12}C$ target is discussed. The $^{12}C$ target is an intermediate situation where the number of target nucleons may be too many for

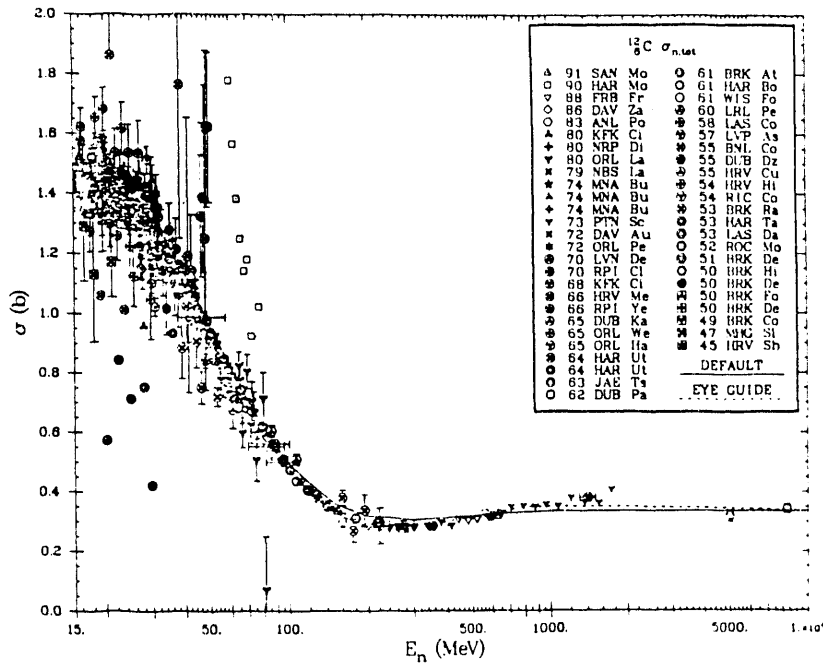


Figure 2: Total cross section for neutrons on carbon. See text for explanation of curves.

few-body analysis and too few for statistical modelling. Codes, admittedly suspect in terms of their validity for $^{12}$C analysis, are used with extensive comparisons with experimental data to help recommend the evaluated data.

For evaluated data files having a low energy upper limit, e.g. 20 MeV, reactions involve the emission of only a few products and the reaction path is generally unique, e.g. (n,$\alpha$) predominates over (n,2d) or (n,n$^3$He). For medium energy data files the nucleon total, elastic scattering, and nonelastic cross sections; multiple particle production cross sections, e.g. (n,xn), and residual nucleus formation cross sections, e.g. $^{12}$C(p,X)$^7$Be, are the practical objectives.

## 2. $^{12}$C Total, Elastic and Nonelastic Data

Curves using nuclear model codes and systematics similar to those developed earlier[5] will be used as a trial curve (labeled DEFAULT) to compare calculation with experiment. The total cross section in the energy range 15 to 10000 MeV is shown in Fig. 2. Because natural carbon is 98.9% $^{12}$C elemental carbon data is interchangeable for $^{12}$C data for such cross sections. The experimental data will not be individually referenced in this report but expanded reference titles for those symbols appearing in the legend box are available from the author and the data are obtainable in computerized form[1]. The DEFAULT curve for the total cross section is quite satisfactory. The agreement can be improved by lowering the curve a bit

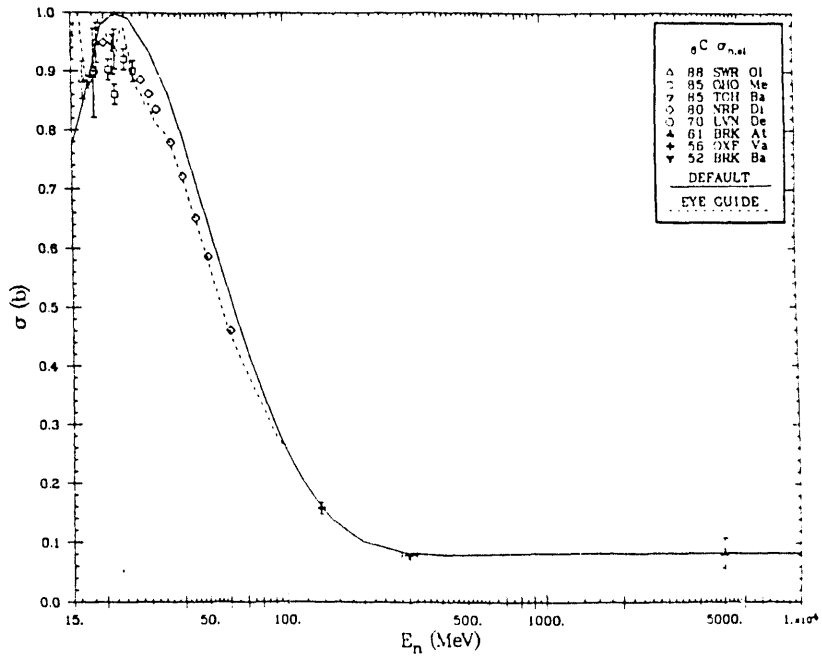


Figure 3: Elastic scattering cross section for neutrons on carbon. See text for explanation of curves.

about 200 MeV and raising the curve a bit about 1000 MeV. Below 32 MeV data from ENDF/B-VI[6] for elemental carbon[7] is used. At 32 MeV the ENDF/B-VI total cross section is 1.306 b.

The elastic scattering cross section over the same energy range is shown in Fig. 3. The agreement between calculation and experiment is excellent for the high energy points available but the curve should be revised downward about 10% below 60 MeV to join ENDF/B-VI smoothly at 32 MeV where the elastic scattering cross section is 0.810 b.

The nonelastic cross section is shown in Fig. 4. Again, the agreement between calculation and experiment is excellent for the high energy points available but the curve should be revised upward about 10% below 60 MeV to join ENDF/B-VI smoothly at 32 MeV where the nonelastic cross section is 0.496 b.

The DEFAULT curve for protons on $^{12}C$ nonelastic cross section shown in Fig. 5 is obtained from optical model calculations using global parameters[5]. Good agreement with an experimental data compilation[8] can be obtained at high energies by about a 5% lowering of the curve above 100 MeV. Below 30 MeV single-particle effects are present which are not modeled in the optical model calculations. The evaluation would follow the eye-guide shown in the figure.

## 3. Residual Nucleus Formation Data

In the work described here for the calculation of residual nucleus formation

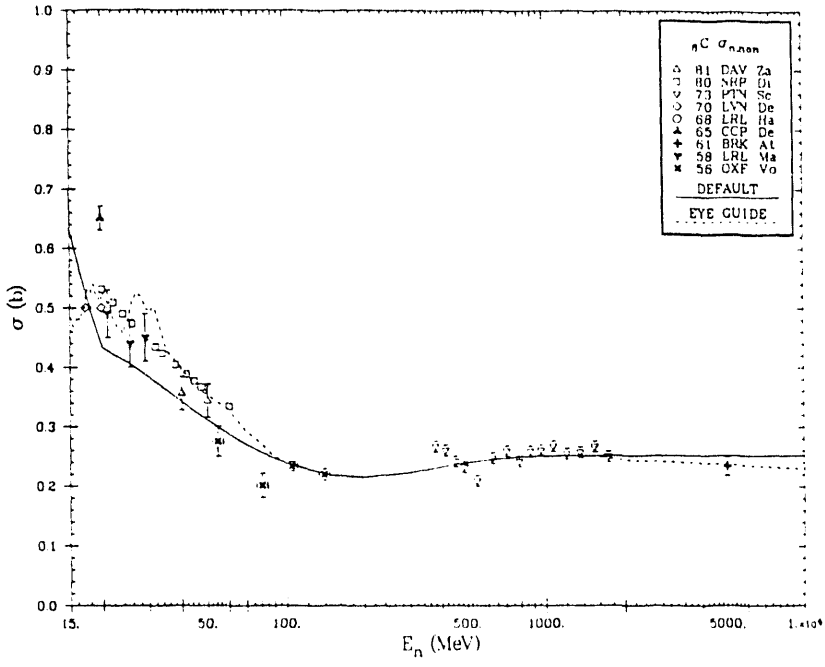


Figure 4: Nonelastic cross section for neutrons on carbon. See text for explanation of curves.

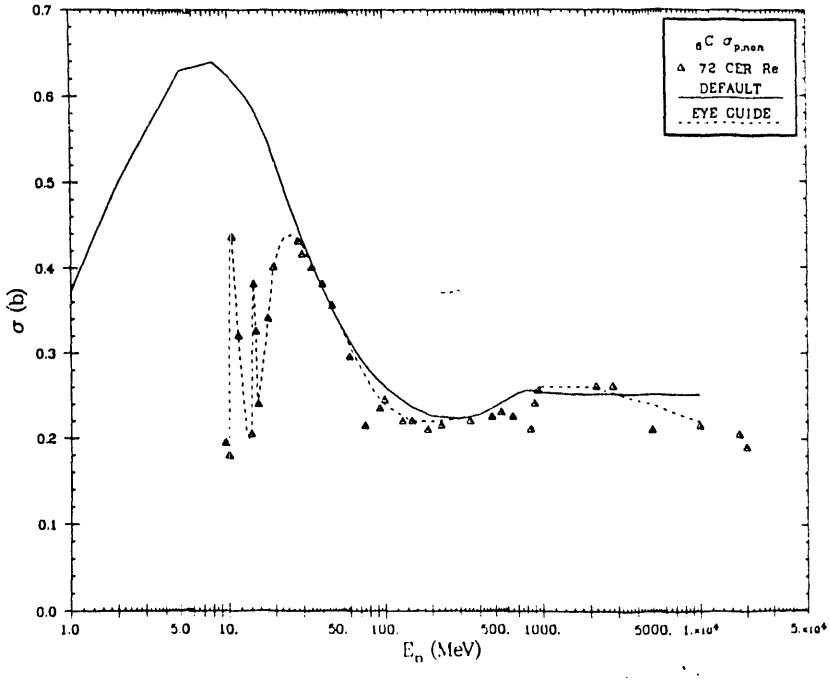


Figure 5: Nonelastic cross section for protons on carbon. See text for explanation of curves.

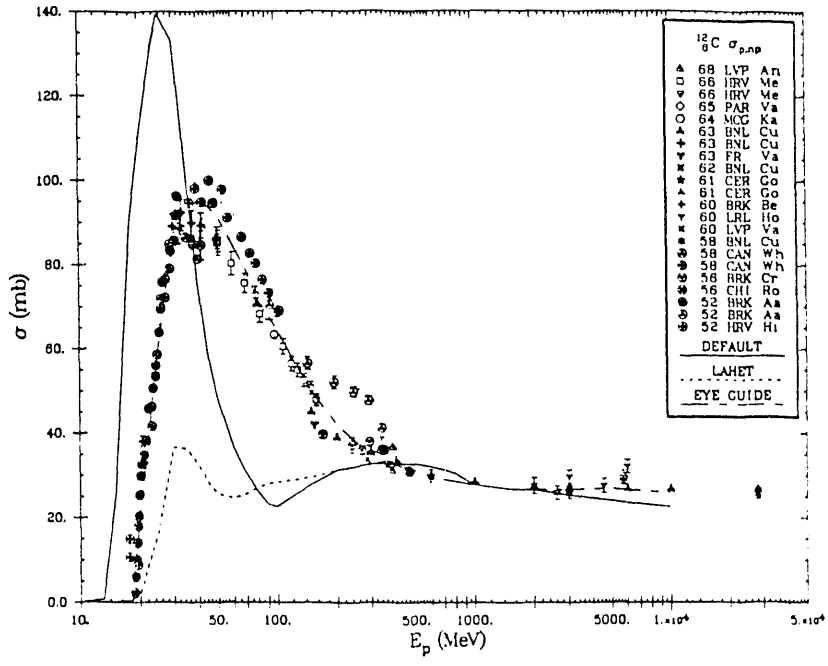


Figure 6: Cross section for the $^{12}C(p,X)^{11}C$ reaction. See text for explanation of curves.

cross sections from neutron- and proton-induced reactions, reliance is placed on two nuclear model codes; (1) a closed form pre-equilibrium plus evaporation code, (modified ALICE[9] code called ALICE-P[5]), and (2) an intra-nuclear-cascade code (LAHET[10]).

In Fig. 6 the experimental data for the $^{12}C(p,X)^{11}C$ reaction is shown with 3 curves. The curve labeled DEFAULT consists of ALICE-P results at and below 100 MeV and LAHET results above 100 MeV smoothly joined at the interface. The LAHET curve is the LAHET results extended to lower energies. At energies above 300 MeV the LAHET results agree quite well with experiment. In the region of the peak at 50 MeV the ALICE-P results are high by about 50% and the LAHET results are low by about 100%. The EYE-GUIDE is a smooth curve drawn through the data. For the de-excitation of light nuclei where the statistical assumptions of the evaporation model are not well satisfied the LAHET code uses the Fermi breakup model which improves the agreement between calculation and experiment for the production of alpha-cluster nuclides, e.g. $^{8}Be$.

The comparison of calculation and experiment for residual nucleus formation cross sections for neutron-induced reactions on $^{12}C$ is limited because of the scarcity

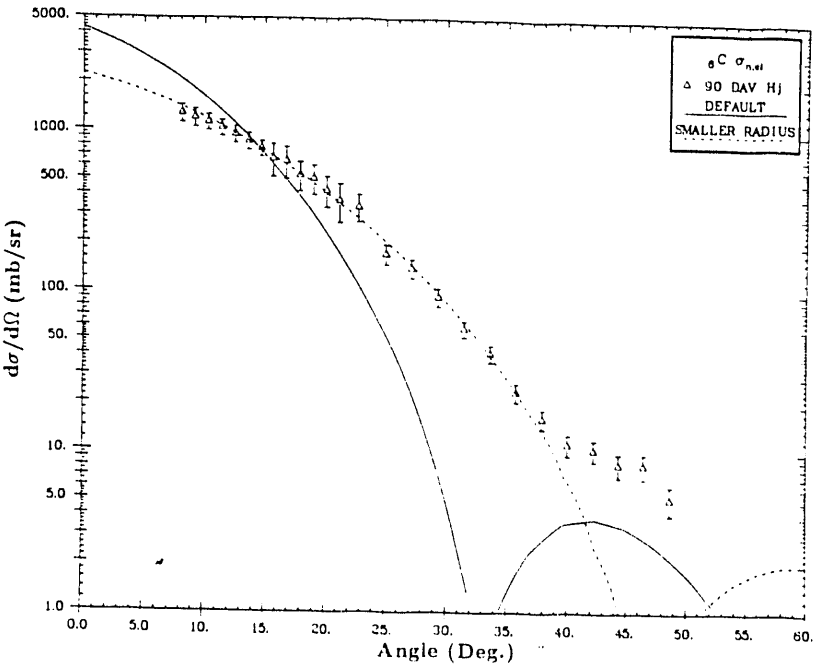


Figure 7: Elastic scattering angular distribution for 65 MeV neutrons on carbon. See text for explanation of curves.

of medium energy neutron reaction data.

## 4. Single- and Double-Differential Data

### *1. Elastic Scattering*

Elastic scattering data for 65 MeV neutrons on carbon in the zero-linear-momentum system are shown in Fig. 7. The DEFAULT curve is based on nuclear systematics[3,11] that is generally valid for small angle scattering. Here, the modeled data is too forward peaked. The second diffraction peak occurs at about the same angle in both the measured and modeled data but the modeled peak magnitude is lower. Reducing the radius in the calculation brings the measured and calculated curves into agreement at forward angles but increases the disagreement at larger angles. These conclusions also hold true in comparisons with measurements of forward peaked elastic neutron scattering from carbon at higher energies.

Elastic scattering of charged particles includes components from Coulomb scattering, nuclear scattering, and the interference between them. For elastic scattering of protons the nuclear elastic scattering is assumed to be similar to neutron elastic scattering.

Data for elastic scattering of nucleons in the forward angles, which are usually the most important ones in transport calculations, can be parameterized by a simple diffraction model. Unless experimental data covering a wide range of inci-

dent energies and scattering angles are available to assist the evaluation, the curves obtained from systematics may be low at back angles.

*1.1. Double-Differential Data*

Experimental data for the energy-angle emission of reaction products is available. Neutron emission data from the proton bombardment of targets in the mass range from carbon to uranium have been analyzed and parameterized by evaporation formulae[12]. The energy-angle distribution for emitted neutrons are also calculated by nuclear model codes and have been compared to nuclear systematics[13]. The systematics have been extended down to about 25 MeV and are used to produce the double-differential neutron emission data for $^{12}C$. In comparison to experiment intra-nuclear-cascade codes under-calculated the emission of high energy neutrons at back angles in (p,xn) reactions but recent versions of LAHET have substantially improved the agreement.

## 5. Conclusions

The author's general approach to producing evaluated data files for neutron- and proton-induced reactions has been described with particular application to a $^{12}C$ target. For a light mass target such as $^{12}C$ the nuclear model calculations can be deficient. The calculations may be of the right order of magnitude but revisions are frequently required to obtain agreement with experimental data. The completed $^{12}C$ evaluations have been given to the National Nuclear Data Center.

## 5. Acknowledgements

This work was performed at Brookhaven National Laboratory and supported by the U.S. Department of Energy.

## 6. References

1. National Nuclear Data Center, Brookhaven National Laboratory, Upton, New York 11973. Tel:(516)282-2901, FAX:-2806, Bitnet:NNDC@BNL, Internet:NNDC@BNLND2.DNE.BNL.GOV On-line access to neutron, charged particle, nuclear structure and radioactive decay data and indices to bibliography.
2. S. Pearlstein, *Summary of the Meeting of the Medium Energy Nuclear Data Working Group*, May 21-22, 1986 Brookhaven Nat. Lab. (BNL-NCS-38404, 1986).
3. S. Pearlstein, *Summary of the Meeting of the Medium Energy Nuclear Data Working Group*, May 27-29, 1987 NASA Langley Res. Ctr. (BNL-NCS-40070, 1987).
4. S. Pearlstein, in *Proc. Int. Conf. on Nuclear Data for Science and Technology*, May 30-June 3, 1988, Mito, p. 1115 (Saikon Pub. 1988).
5. S. Pearlstein, *Astrophysics J.* **346** (1989) 1049.

6. ENDF/B, *Evaluated Nuclear Data File/ Version B.* Distributed by the National Nuclear Data Center.

7. C. Y. Fu, E. J. Axton and F. G. Perey, *ENDF/B-VI, Evaluated Data for 0-32 MeV Neutrons incident on Elemental Carbon*, Completed August 1989. See Refs. 1 and 6.

8. P. U. Renberg et. al., *Nucl. Phys.* **A183** (1972) 81.

9. M. Blann, *Code ALICE/85/300* and succeeding versions. Lawrence Livermore Nat. Lab. (UCID-20169 1985).

10. R. E. Prael and H. Lichtenstein, in *User Guide to LCS: The LAHET Code System*, Las Alamos Nat. Lab. (LA-UR-89-3014 1989).

11. S. Pearlstein, *Nucl. Sci. Eng.* **49** (1972) 162.

12. S. Pearlstein, *Nucl. Sci. Eng.* **95** (1987) 116.

13. S. Pearlstein, *An Intercomparison of Medium Energy Cross Section Codes* , Brookhaven Nat. Lab. (BNL-NCS-52155, 1988).

DATE
FILMED
02/01/93