EVALUATION OF p + 184W CROSS SECTIONS FOR THE ENERGY RANGE 2 to 150 MeV

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This evaluation provides a complete representation of the nuclear data needed for transport, damage, heating, radioactivity, and shielding applications over the incident neutron energy range from 2 to 150 MeV.

The evaluation utilizes MF = 3 [MT=2 and MT=5] and MF=6 [MT=2 and MT=5] to represent all reaction data. Production cross sections and emission spectra are given for neutrons, protons, deuterons, tritons, alpha particles, gamma rays, and all residual nuclides produced with non-negligible cross sections (A>5) in the reaction chains. To summarize, the ENDF sections with non-zero data are:

MF=3	MT= 2	Integral of nuclear plus interference components of the elastic scattering cross section
	MT= 5	Sum of binary (n,n') and (n,x) reactions
MF=6	MT= 2	Elastic angular distributions given as ratios of the differential nuclear-plus-interference to the integrated value.
	MT= 5	Production cross sections and energy-angle distributions for emission neutrons, protons, deuterons, and alphas; and angle-integrated spectra for gamma rays and residual nuclei that are stable against particle emission

The evaluation is based on nuclear model calculations that have been benchmarked to experimental data, especially for n + W, n + Ta, p + Ta, and p + W reactions (Ch96a). We use the GNASH code system (Yo92), which utilizes Hauser-Feshbach statistical, preequilibrium and direct-reaction theories. Coupled-channels and spherical optical model calculations are used to obtain particle transmission coefficients for the Hauser-Feshbach calculations, as well as for the elastic neutron angular distributions.

Cross sections and spectra for producing individual residual nuclei are included for reactions that exceed a cross section of approximately 1 nb at any energy. The energy-angle-correlations for all outgoing particles are based on Kalbach systematics (Ka88).

A coupled-channels neutron optical model potential based on earlier work to 100 MeV (Yo90) is utilized to 80 MeV, and the global spherical optical model potential of Madland (Ma88) is used at higher energies. For protons, the Beccetti-Greenlees potential (Be69) is utilized below 20 MeV, and the Madland Semmering potential (Ma88) at higher energies. The Perey potential (Pe63) is used for deuterons, and the Beccetti-Greenlees potential (Be71) for tritons. The ECIS79 code (Ra72) was used for the coupled-channels optical model calculations, and the SCAT2 code (Be92) was utilized for the spherical optical model calculations. Minor normalizations were made to the reaction cross sections and transmission coefficients to produce

agreement with the (sparse) measurements for W and values inferred from systematics of proton and neutron reaction cross sections from measurements on other targets. The same reaction cross sections are used for both proton- and neutron-induced reactions on W isotopes.

A model was developed to calculate the energy distributions of all recoil nuclei in the GNASH calculations (Ch96b). The recoil energy distributions are represented in the laboratory system in MT=5, MF=6, and are given as isotropic in the lab system. Note that all other data in MT=5,MF=6 are given in the center-of-mass system. This method of representation requires a modification of the original ENDF-6 format, i.e., we use LCT=3 with LAW 1 to indicate that data for the heavy recoils are in the lab system but all other reactions are in the cm system.

Preequilibrium corrections were performed in the course of the GNASH calculations using the exciton model of Kalbach (Ka77, Ka85), validated by comparison with calculations using Feshbach, Kerman, Koonin (FKK) theory [Ch93]. Discrete level data from nuclear data sheets were matched to continuum level densities using the formulation of Ignatyuk (Ig75) and pairing and shell parameters from the Cook (Co67) analysis. Neutron and charged-particle transmission coefficients were obtained from the optical potentials, as discussed above. Gamma-ray transmission coefficients were calculated using the Kopecky-Uhl model (Ko90).

MT=2 elastic scattering data in MF=3 and MF=6 are based on optical model calculations with the SCAT2 code (Be92). We have made use of the "nuclear-plus-interference" option in MF=6, which corresponds to LAW=5, LTP=12, and the appropriate integrated cross section is stored in MF=3. Note that because of the interference effect, the tabulations in both MF=6 and MF=3 can be negative at some energies and angles.

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REFERENCES

[Ar80]. E.D. Arthur, P.G. Young, A.B. Smith, and C. Philis, ENDF/B-V.2 evaluation, carried over to ENDF/B-VI.

[Be69]. F.D. Becchetti, Jr., and G.W. Greenlees, Phys. Rev. 182, 1190 (1969).

[Be71]. F.D. Becchetti, Jr., and G.W. Greenlees in "Polarization Phenomena in Nuclear Reactions," (Ed: H.H. Barschall and W. Haeberli, The University of Wisconsin Press, 1971) p.682.

[Be92]. O. Bersillon, "SCAT2 - A Spherical Optical Model Code," in Proc. ICTP Workshop on Computation and Analysis of Nuclear Data Relevant to Nuclear Energy and Safety, 10 February-13 March, 1992, Trieste, Italy, to be published in World Scientific Press, and Progress Report of the Nuclear Physics Division, Bruyeres-le-Chatel 1977, CEA-N-2037, p.111 (1978).

[Ch93]. M.B. Chadwick and P G. Young, "Feshbach-Kerman-Koonin Analysis of 93Nb Reactions: P --> Q Transitions and Reduced Importance of Multistep Compound Emission," Phys. Rev. C 47, 2255 (1993).

[Ch96a]. M. B. Chadwick and P. G. Young, "GNASH Calculations of

n,p + 182,183,184,186W and Benchmarking of Results" in APT PROGRESS REPORT: 1 August - 1 September 1996, internal Los Alamos National Laboratory memo T-2-96/MS-40, 7 Sept. 1996 from R.E. MacFarlane to L. Waters.

[Ch96b]. M. B. Chadwick, P. G. Young, R. E. MacFarlane, and A. J. Koning, "High-Energy Nuclear Data Libraries for Accelerator-Driven Technologies: Calculational Method for Heavy Recoils," Proc. of 2nd Int. Conf. on Accelerator Driven Transmutation Technology and Applications, Kalmar, Sweden, 3-7 June 1996.

[Co67]. J.L. Cook, H. Ferguson, and A.R. Musgrove, "Nuclear Level Densities in Intermediate and Heavy Nuclei," Aust.J.Phys. 20, 477 (1967).

[Fi93]. R. Finlay et al., Phys. Rev. 47, 237 (1993).

[Ig75]. A.V. Ignatyuk, G.N. Smirenkin, and A.S. Tishin, "Phenomenological Description of the Energy Dependence of the Level Density Parameter," Sov. J. Nucl. Phys. 21, 255 (1975).

[Ka77]. C. Kalbach, "The Griffin Model, Complex Particles and Direct Nuclear Reactions," Z.Phys.A 283, 401 (1977).

[Ka85]. C. Kalbach, "PRECO-D2: Program for Calculating Preequilibrium and Direct Reaction Double Differential Cross Sections," Los Alamos National Laboratory report LA-10248-MS (1985).

[Ka88]. C. Kalbach, "Systematics of Continuum Angular Distributions: Extensions to Higher Energies," Phys.Rev.C 37, 2350 (1988); see also C. Kalbach and F. M. Mann, "Phenomenology of Continuum Angular Distributions. I. Systematics and Parameterization," Phys.Rev.C 23, 112 (1981).

[Ko90]. J. Kopecky and M. Uhl, "Test of Gamma-Ray Strength Functions in Nuclear Reaction Model Calculations," Phys.Rev.C 42, 1941 (1990).

[Ma88]. D.G. Madland, "Recent Results in the Development of a Global Medium-Energy Nucleon-Nucleus Optical-Model Potential," Proc. OECD/NEANDC Specialist's Mtg. on Preequilibrium Nuclear Reactions, Semmering, Austria, 10-12 Feb. 1988, NEANDC-245 'U' (1988).

[Pe63]. C. M. Perey and F. G. Perey, Phys. Rev. 132, 755 (1963).

[Ra72]. J. Raynal, "Optical Model and Coupled-Channels Calculations in Nuclear Physics," IAEA SMR-9/8 (1972) p. 281.

[Yo90]. P.G. Young, E.D. Arthur, M. Bozoian, T.R. England, G.M. Hale, R.J. LaBauve, R.C. Little, R.E. MacFarlane, D.G. Madland, R.T. Perry, and W.B. Wilson, "Transport Data Libraries for Incident Proton and Neutron Energies to 100 MeV," Los Alamos National Laboratory report LA-11753-MS (July 1990).

[Yo92]. P.G. Young, E.D. Arthur, and M.B. Chadwick, "Comprehensive Nuclear Model Calculations: Introduction to the Theory and Use of the GNASH Code," LA-12343-MS (1992).

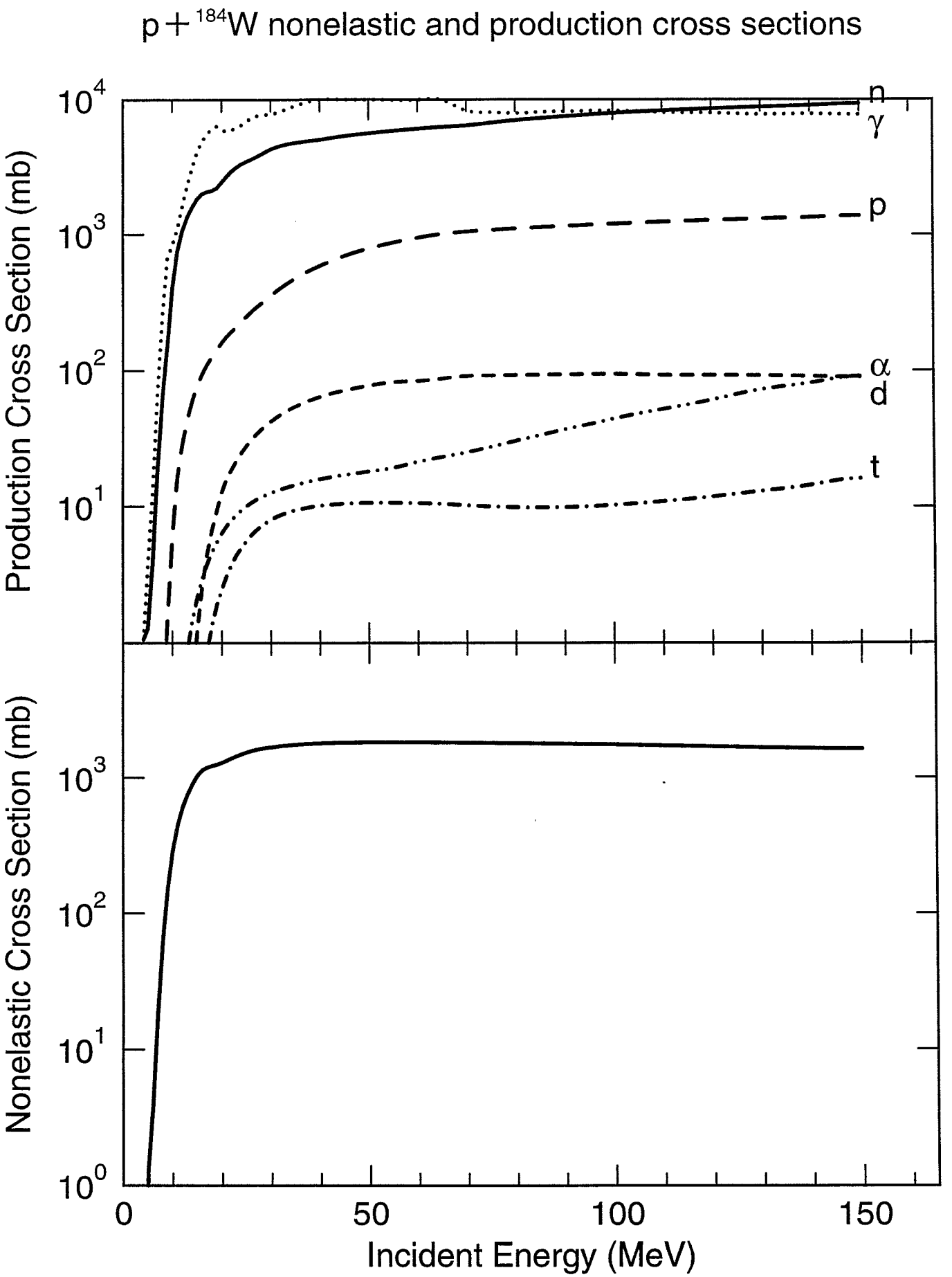
74184 = TARGET 1000Z+A (if A=0 then elemental)
1001 = PROJECTILE 1000Z+A
Nonelastic, elastic, and Production cross sections for A<5 ejectiles in barns:

Energy	nonelas	elastic	neutron	proton	deuteron	triton	helium3	alpha	gamma
3.000E+00	1.000E-20	0.000E+00	1.000E-20	1.000E-20	0.000E+00	0.000E+00	0.000E+00	1.000E-20	1.000E-20
4.000E+00	1.689E-05	0.000E+00	1.633E-05	6.767E-12	0.000E+00	0.000E+00	0.000E+00	3.598E-07	3.679E-05
5.000E+00	1.289E-03	0.000E+00	1.276E-03	9.543E-09	0.000E+00	0.000E+00	0.000E+00	6.990E-07	3.542E-03
6.000E+00	3.940E-03	0.000E+00	3.907E-03	1.056E-06	0.000E+00	0.000E+00	0.000E+00	2.690E-06	1.259E-02
7.000E+00	1.915E-02	0.000E+00	1.902E-02	1.872E-05	0.000E+00	0.000E+00	0.000E+00	7.414E-06	6.997E-02
8.000E+00	6.458E-02	0.000E+00	6.407E-02	2.431E-04	7.388E-10	0.000E+00	0.000E+00	1.920E-05	2.606E-01
9.000E+00	1.537E-01	0.000E+00	1.549E-01	1.531E-03	1.200E-09	1.270E-08	0.000E+00	4.724E-05	6.632E-01
1.000E+01	2.875E-01	0.000E+00	4.069E-01	6.053E-03	4.048E-07	6.240E-08	0.000E+00	1.119E-04	8.353E-01
1.100E+01	4.462E-01	0.000E+00	7.440E-01	1.652E-02	3.774E-06	6.657E-07	0.000E+00	2.449E-04	1.088E+00
1.200E+01	6.053E-01	0.000E+00	1.061E+00	2.889E-02	1.235E-05	3.070E-06	0.000E+00	4.865E-04	1.606E+00
1.300E+01	7.529E-01	0.000E+00	1.336E+00	4.341E-02	8.508E-05	1.648E-05	0.000E+00	8.787E-04	2.288E+00
1.400E+01	8.956E-01	0.000E+00	1.590E+00	5.981E-02	3.853E-04	6.862E-05	0.000E+00	1.433E-03	3.106E+00
1.500E+01	1.033E+00	0.000E+00	1.828E+00	7.714E-02	1.201E-03	2.079E-04	0.000E+00	2.134E-03	4.025E+00
1.600E+01	1.135E+00	0.000E+00	1.997E+00	9.397E-02	2.550E-03	4.752E-04	0.000E+00	2.934E-03	4.886E+00
1.700E+01	1.188E+00	0.000E+00	2.070E+00	1.102E-01	4.409E-03	8.560E-04	0.000E+00	3.772E-03	5.553E+00
1.800E+01	1.221E+00	0.000E+00	2.112E+00	1.258E-01	6.682E-03	1.334E-03	0.000E+00	4.614E-03	6.109E+00
1.900E+01	1.250E+00	0.000E+00	2.209E+00	1.417E-01	9.250E-03	1.888E-03	0.000E+00	5.465E-03	6.367E+00
2.000E+01	1.289E+00	0.000E+00	2.441E+00	1.601E-01	1.272E-02	2.467E-03	0.000E+00	6.347E-03	5.976E+00
2.200E+01	1.394E+00	0.000E+00	2.933E+00	1.936E-01	1.878E-02	3.759E-03	0.000E+00	7.960E-03	5.974E+00
2.400E+01	1.492E+00	0.000E+00	3.323E+00	2.284E-01	2.483E-02	4.992E-03	0.000E+00	9.360E-03	6.486E+00
2.600E+01	1.577E+00	0.000E+00	3.605E+00	2.699E-01	3.094E-02	6.149E-03	0.000E+00	1.064E-02	7.282E+00
2.800E+01	1.638E+00	0.000E+00	3.924E+00	3.110E-01	3.678E-02	7.144E-03	0.000E+00	1.170E-02	7.687E+00
3.000E+01	1.681E+00	0.000E+00	4.279E+00	3.554E-01	4.236E-02	7.991E-03	0.000E+00	1.261E-02	7.805E+00
3.500E+01	1.756E+00	0.000E+00	4.786E+00	4.762E-01	5.462E-02	9.383E-03	0.000E+00	1.442E-02	9.021E+00
4.000E+01	1.800E+00	0.000E+00	5.060E+00	5.880E-01	6.437E-02	1.013E-02	0.000E+00	1.591E-02	9.989E+00
4.500E+01	1.822E+00	0.000E+00	5.378E+00	6.970E-01	7.176E-02	1.050E-02	0.000E+00	1.712E-02	9.982E+00
5.000E+01	1.830E+00	0.000E+00	5.643E+00	7.910E-01	7.762E-02	1.063E-02	0.000E+00	1.816E-02	9.958E+00
5.500E+01	1.832E+00	0.000E+00	5.891E+00	8.734E-01	8.233E-02	1.064E-02	0.000E+00	1.933E-02	9.931E+00
6.000E+01	1.830E+00	0.000E+00	6.107E+00	9.468E-01	8.405E-02	1.056E-02	0.000E+00	2.136E-02	9.984E+00
6.500E+01	1.826E+00	0.000E+00	6.299E+00	1.011E+00	8.749E-02	1.043E-02	0.000E+00	2.323E-02	9.981E+00
7.000E+01	1.819E+00	0.000E+00	6.455E+00	1.051E+00	9.135E-02	1.019E-02	0.000E+00	2.512E-02	8.279E+00
7.500E+01	1.809E+00	0.000E+00	6.749E+00	1.082E+00	9.204E-02	9.979E-03	0.000E+00	2.757E-02	8.036E+00
8.000E+01	1.799E+00	0.000E+00	7.036E+00	1.108E+00	9.252E-02	9.852E-03	0.000E+00	3.047E-02	7.908E+00
8.500E+01	1.788E+00	0.000E+00	7.280E+00	1.134E+00	9.311E-02	9.817E-03	0.000E+00	3.351E-02	8.090E+00
9.000E+01	1.778E+00	0.000E+00	7.500E+00	1.157E+00	9.349E-02	9.871E-03	0.000E+00	3.692E-02	8.147E+00
9.500E+01	1.768E+00	0.000E+00	7.723E+00	1.181E+00	9.402E-02	1.001E-02	0.000E+00	4.045E-02	8.207E+00
1.000E+02	1.756E+00	0.000E+00	7.929E+00	1.201E+00	9.427E-02	1.025E-02	0.000E+00	4.433E-02	8.257E+00
1.100E+02	1.727E+00	0.000E+00	8.261E+00	1.240E+00	9.263E-02	1.089E-02	0.000E+00	5.199E-02	8.015E+00
1.200E+02	1.699E+00	0.000E+00	8.556E+00	1.275E+00	9.241E-02	1.183E-02	0.000E+00	6.106E-02	7.954E+00
1.300E+02	1.672E+00	0.000E+00	8.823E+00	1.308E+00	9.186E-02	1.303E-02	0.000E+00	7.261E-02	7.758E+00
1.400E+02	1.648E+00	0.000E+00	9.084E+00	1.342E+00	9.089E-02	1.446E-02	0.000E+00	8.119E-02	7.842E+00
1.500E+02	1.631E+00	0.000E+00	9.350E+00	1.379E+00	8.960E-02	1.610E-02	0.000E+00	9.087E-02	7.725E+00

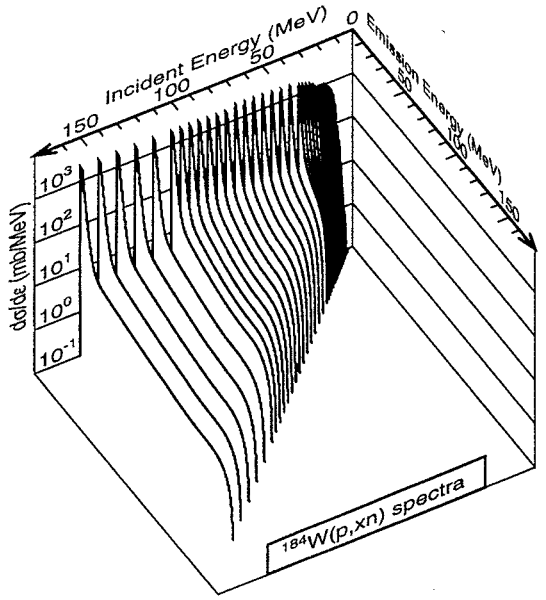
74184 = TARGET 1000Z+A (if A=0 then elemental)
1001 = PROJECTILE 1000Z+A
Aver. lab emission energies for A<5 ejectiles in MeV:

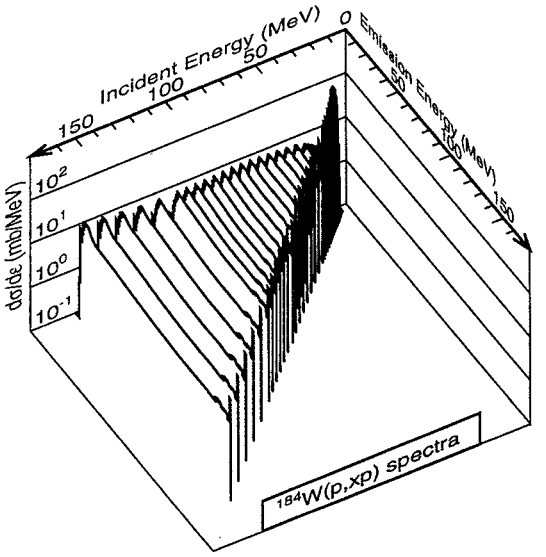
Energy	neutron	proton	deuteron	triton	helium3	alpha	gamma
3.000E+00	4.682E-01	8.911E-05	0.000E+00	0.000E+00	0.000E+00	9.511E+00	3.419E-01
4.000E+00	8.397E-01	3.658E+00	0.000E+00	0.000E+00	0.000E+00	1.047E+01	4.571E-01
5.000E+00	1.026E+00	4.621E+00	0.000E+00	0.000E+00	0.000E+00	1.108E+01	6.590E-01
6.000E+00	1.097E+00	5.689E+00	0.000E+00	0.000E+00	0.000E+00	1.210E+01	8.384E-01
7.000E+00	1.120E+00	6.682E+00	0.000E+00	0.000E+00	0.000E+00	1.279E+01	9.975E-01
8.000E+00	1.170E+00	7.671E+00	2.733E+00	0.000E+00	0.000E+00	1.362E+01	1.135E+00
9.000E+00	1.240E+00	8.648E+00	3.592E+00	3.711E+00	0.000E+00	1.441E+01	1.223E+00
1.000E+01	1.090E+00	9.608E+00	4.536E+00	4.531E+00	0.000E+00	1.518E+01	1.094E+00
1.100E+01	1.144E+00	1.055E+01	5.225E+00	5.057E+00	0.000E+00	1.598E+01	7.907E-01
1.200E+01	1.267E+00	1.143E+01	5.986E+00	5.749E+00	0.000E+00	1.672E+01	6.986E-01
1.300E+01	1.389E+00	1.226E+01	7.032E+00	6.794E+00	0.000E+00	1.740E+01	7.443E-01
1.400E+01	1.492E+00	1.302E+01	7.946E+00	7.525E+00	0.000E+00	1.802E+01	8.252E-01
1.500E+01	1.579E+00	1.373E+01	8.792E+00	8.301E+00	0.000E+00	1.859E+01	9.079E-01
1.600E+01	1.665E+00	1.438E+01	9.562E+00	8.995E+00	0.000E+00	1.912E+01	9.837E-01
1.700E+01	1.762E+00	1.500E+01	1.031E+01	9.634E+00	0.000E+00	1.962E+01	1.050E+00
1.800E+01	1.865E+00	1.560E+01	1.105E+01	1.024E+01	0.000E+00	2.008E+01	1.104E+00
1.900E+01	1.925E+00	1.619E+01	1.177E+01	1.081E+01	0.000E+00	2.052E+01	1.111E+00
2.000E+01	1.909E+00	1.685E+01	1.255E+01	1.131E+01	0.000E+00	2.100E+01	1.082E+00
2.200E+01	1.989E+00	1.789E+01	1.391E+01	1.238E+01	0.000E+00	2.190E+01	9.193E-01
2.400E+01	2.132E+00	1.874E+01	1.524E+01	1.341E+01	0.000E+00	2.277E+01	8.523E-01
2.600E+01	2.290E+00	1.944E+01	1.654E+01	1.442E+01	0.000E+00	2.360E+01	8.908E-01
2.800E+01	2.403E+00	2.018E+01	1.783E+01	1.542E+01	0.000E+00	2.439E+01	9.013E-01
3.000E+01	2.492E+00	2.096E+01	1.911E+01	1.640E+01	0.000E+00	2.516E+01	8.548E-01
3.500E+01	2.856E+00	2.307E+01	2.234E+01	1.868E+01	0.000E+00	2.696E+01	8.568E-01

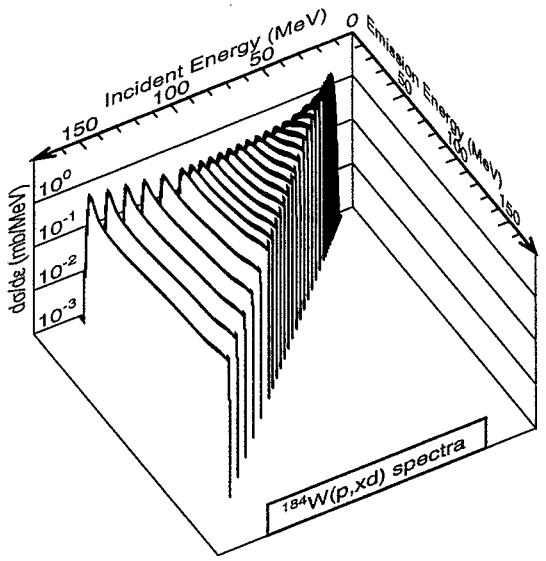
4.000E+01	3.247E+00	2.534E+01	2.562E+01	2.092E+01	0.000E+00	2.846E+01	9.348E-01
4.500E+01	3.576E+00	2.777E+01	2.888E+01	2.315E+01	0.000E+00	2.983E+01	9.077E-01
5.000E+01	3.883E+00	3.012E+01	3.209E+01	2.537E+01	0.000E+00	3.105E+01	8.824E-01
5.500E+01	4.169E+00	3.247E+01	3.523E+01	2.755E+01	0.000E+00	3.193E+01	8.838E-01
6.000E+01	4.452E+00	3.476E+01	3.792E+01	2.967E+01	0.000E+00	3.182E+01	8.999E-01
6.500E+01	4.726E+00	3.699E+01	4.099E+01	3.175E+01	0.000E+00	3.182E+01	9.062E-01
7.000E+01	5.001E+00	3.926E+01	4.453E+01	3.360E+01	0.000E+00	3.175E+01	1.161E+00
7.500E+01	5.150E+00	4.137E+01	4.753E+01	3.519E+01	0.000E+00	3.126E+01	1.168E+00
8.000E+01	5.294E+00	4.348E+01	5.050E+01	3.648E+01	0.000E+00	3.060E+01	1.173E+00
8.500E+01	5.460E+00	4.554E+01	5.345E+01	3.751E+01	0.000E+00	3.002E+01	1.171E+00
9.000E+01	5.633E+00	4.755E+01	5.636E+01	3.816E+01	0.000E+00	2.938E+01	1.184E+00
9.500E+01	5.799E+00	4.943E+01	5.923E+01	3.853E+01	0.000E+00	2.884E+01	1.179E+00
1.000E+02	5.957E+00	5.136E+01	6.204E+01	3.852E+01	0.000E+00	2.828E+01	1.184E+00
1.100E+02	6.274E+00	5.523E+01	6.685E+01	3.776E+01	0.000E+00	2.738E+01	1.202E+00
1.200E+02	6.592E+00	5.880E+01	7.196E+01	3.616E+01	0.000E+00	2.642E+01	1.210E+00
1.300E+02	6.915E+00	6.215E+01	7.667E+01	3.410E+01	0.000E+00	2.522E+01	1.234E+00
1.400E+02	7.237E+00	6.529E+01	8.094E+01	3.190E+01	0.000E+00	2.500E+01	1.212E+00
1.500E+02	7.563E+00	6.826E+01	8.466E+01	2.978E+01	0.000E+00	2.464E+01	1.219E+00

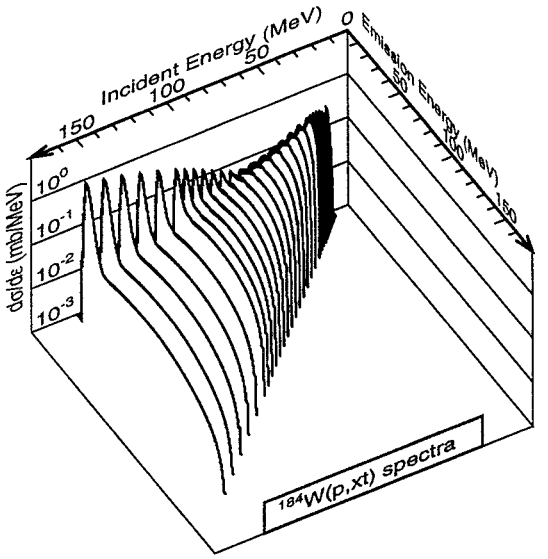

p + 184W nonelastic and production cross sections
Production Cross Section (mb)
Nonelastic Cross Section (mb)
Incident Energy (MeV)
n
γ
p
α
d
t
10^4
10^3
10^2
10^1
10^0
0
50
100
150

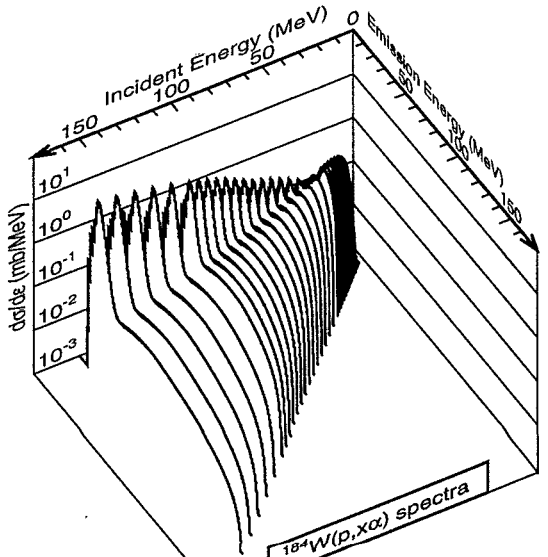
p + ^{184}W angle-integrated emission spectra

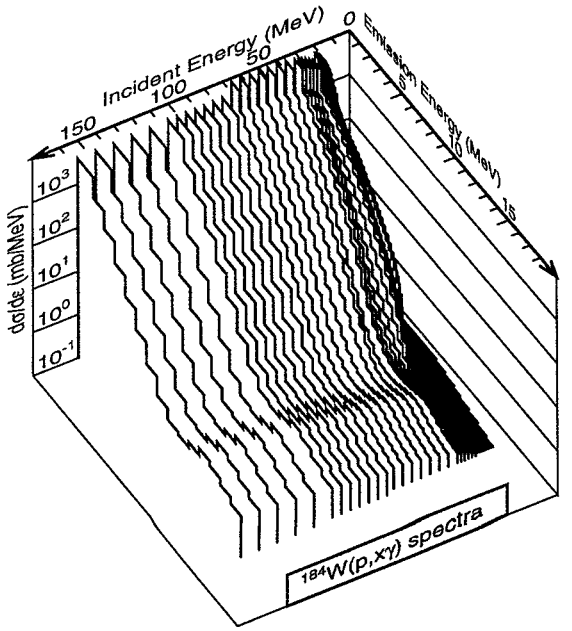




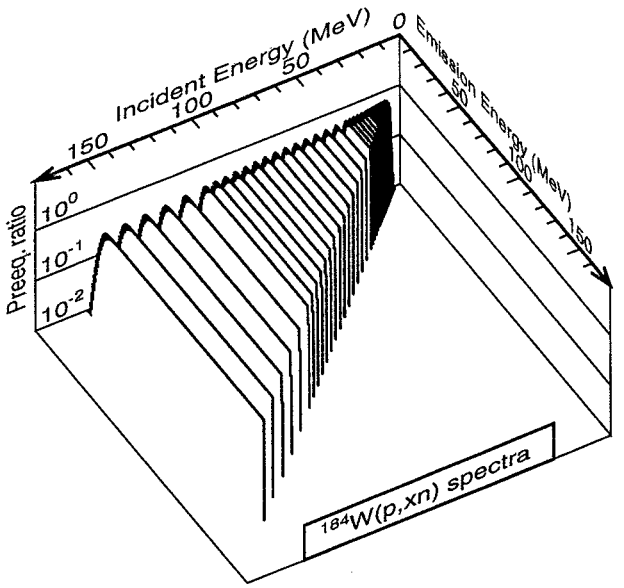


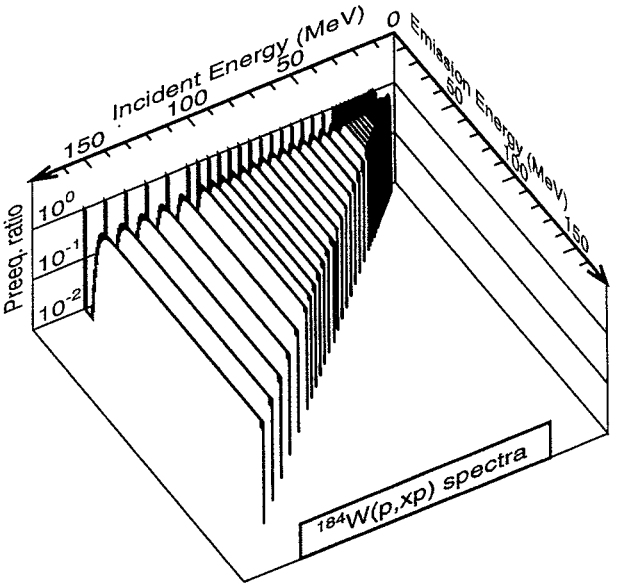


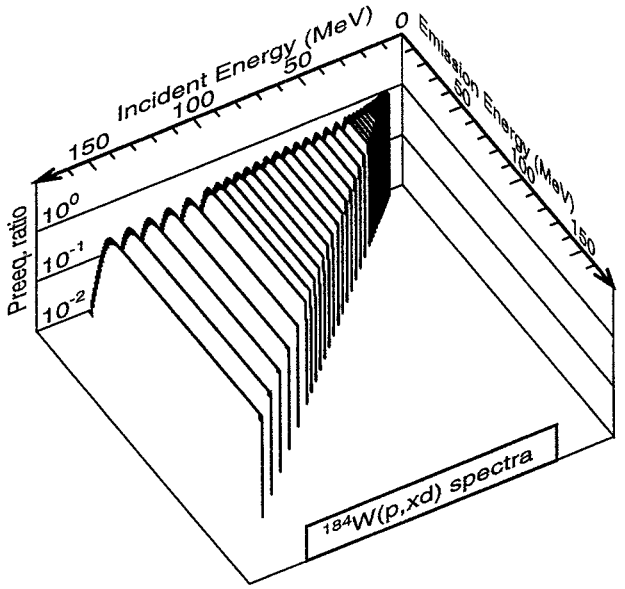


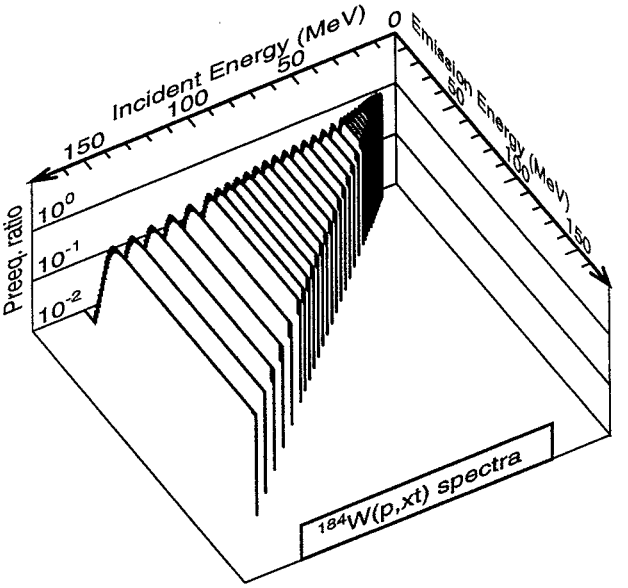


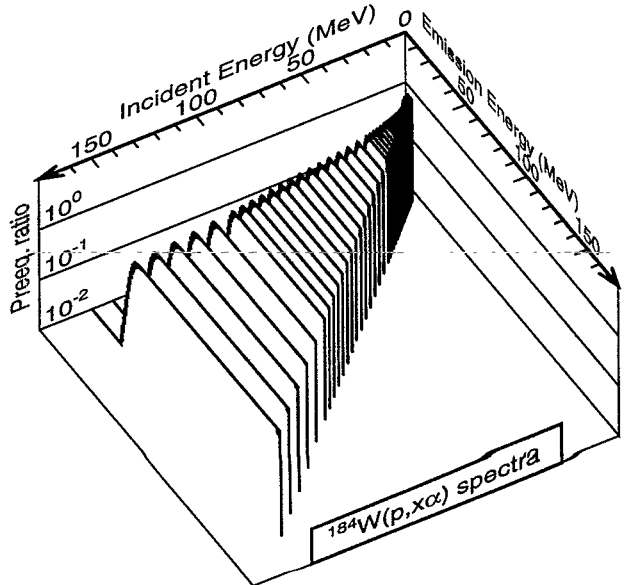
p + ^{184}W Kalbach preequilibrium ratios

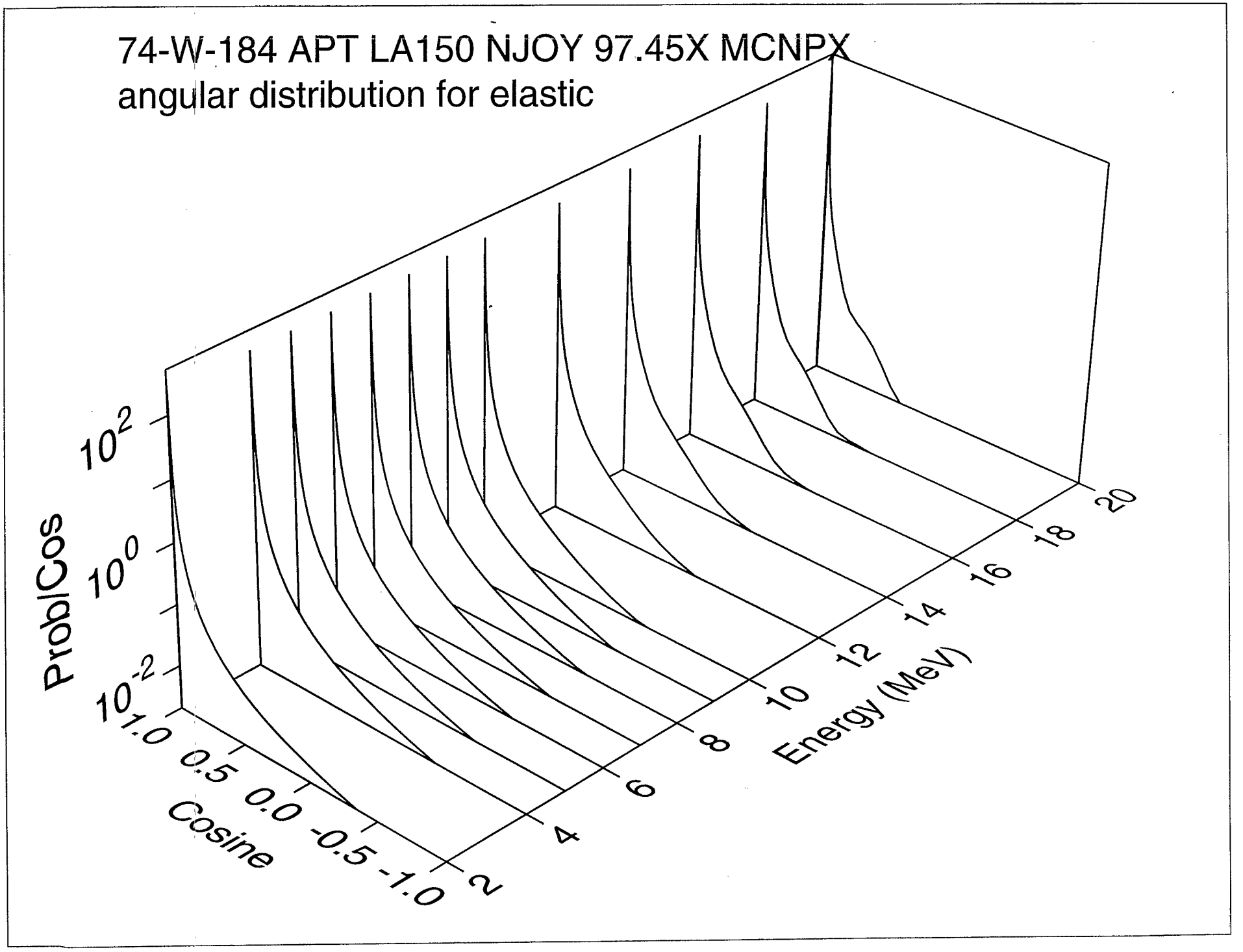


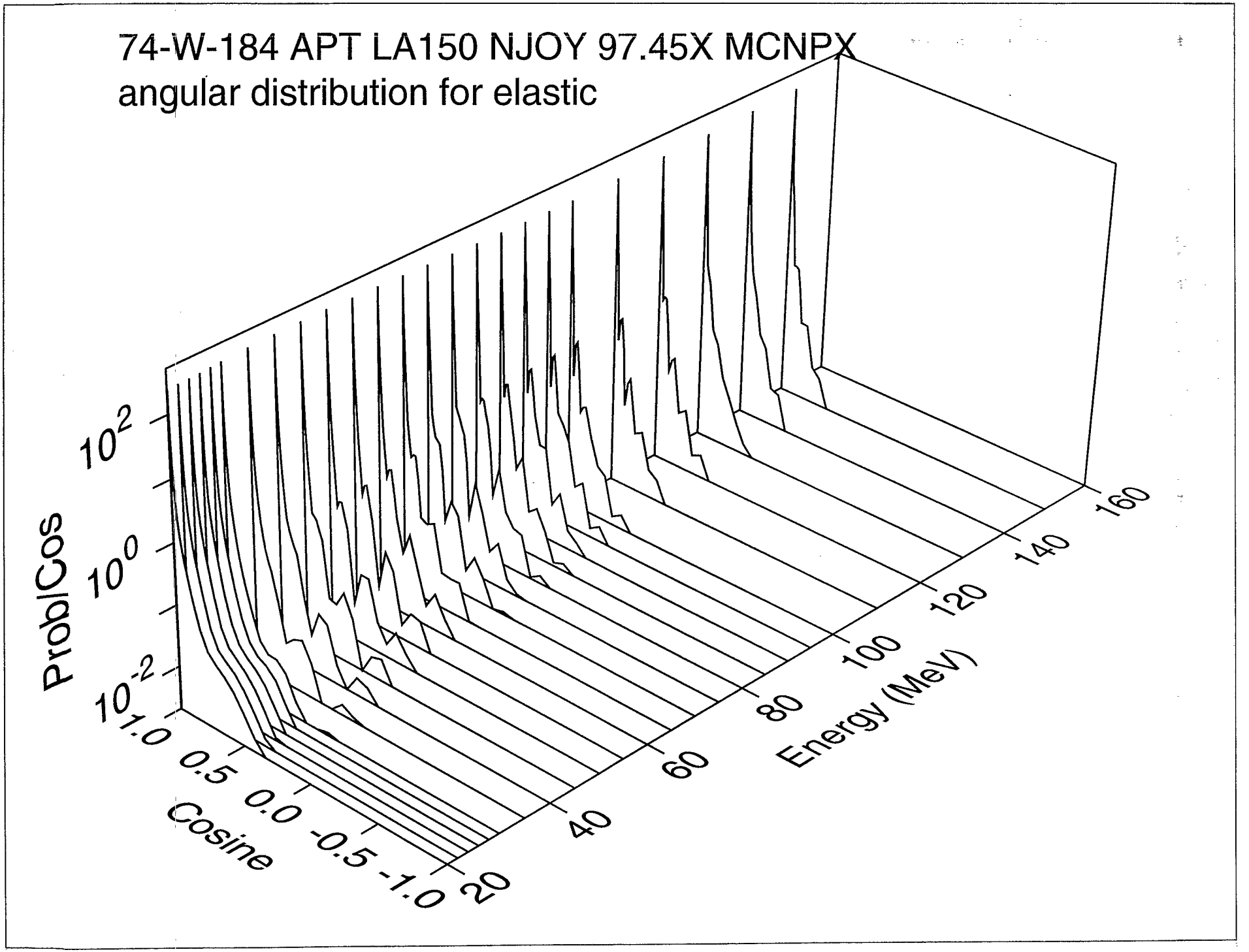


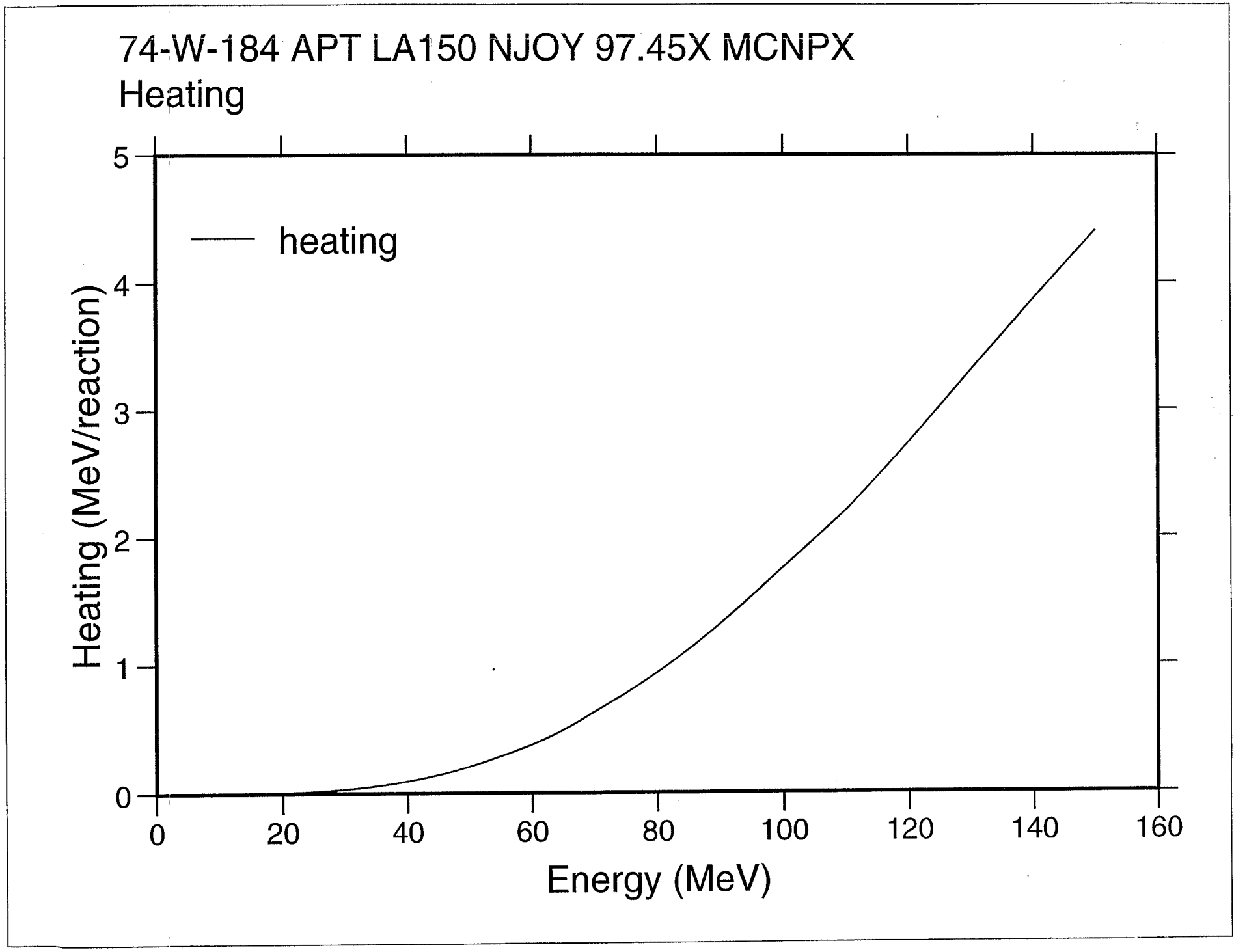







74-W-184 APT LA150 NJOY 97.45X MCNPX
angular distribution for elastic
ProbCos
10^2
10^0
10^{-2}
Cosine
1.0
0.5
0.0
-0.5
-1.0
Energy (MeV)
2
4
6
8
10
12
14
16
18
20


74-W-184 APT LA150 NJOY 97.45X MCNPX
angular distribution for elastic
Prob/Cos
10^2
10^0
10^{-2}
Cosine
1.0
0.5
0.0
-0.5
-1.0
Energy (MeV)
20
40
60
80
100
120
140
160


74-W-184 APT LA150 NJOY 97.45X MCNPX
Heating
heating
Heating (MeV/reaction)
Energy (MeV)
0
1
2
3
4
5
0
20
40
60
80
100
120
140
160