EVALUATION OF p + 31P CROSS SECTIONS FOR THE ENERGY RANGE 1 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 proton energy range from 1 to 150 MeV. The evaluation utilizes MF=6, 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 (A>5) in the reaction chains. To summarize, the ENDF sections with non-zero data above are:

MF=3	MT= 2	Integral of nuclear plus interference components of the elastic scattering cross section
	MT= 5	Sum of binary (p,n') and (p,x) reactions
MF=6	MT= 2	Elastic (p,p) 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 + P31 and p + P31 reactions (Ch98). We use the GNASH code system (Yo92), which utilizes Hauser-Feshbach statistical, preequilibrium and direct-reaction theories. Spherical optical model calculations are used to obtain particle transmission coefficients for the Hauser-Feshbach calculations, as well as for the elastic proton angular distributions.

Cross sections and spectra for producing individual residual nuclei are included for reactions. The energy-angle-correlations for all outgoing particles are based on Kalbach systematics (Ka88).

A model was developed to calculate the energy distributions of all recoil nuclei in the GNASH calculations (Ch96a). The recoil energy distributions are represented in the laboratory system in MT=5, MF=6, and are given as isotropic in the lab system. All other data in MT=5,MF=6 are given in the center-of-mass system. This method of representation utilizes the LCT=3 option approved at the November, 1996, CSEWG meeting.

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 et al. (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 below. Gamma-ray transmission

coefficients were calculated using the Kopecky-Uhl model (Ko90).

SPECIFIC INFORMATION CONCERNING THE P-31 EVALUATION

For incident neutrons the Wilmore-Hodgson [Wi64] optical potential was used below 20 MeV and the Madland medium [Ma88] energy potential was used at higher energies. Above 130 MeV the reaction cross section, and corresponding transmission coefficients, were renormalized to agree with the evaluated reaction cross section of [Ch96b]. For incident protons the Becchetti-Greenlees [Be69] potential was used below 20 MeV, and the Madland potential at higher energies. Above 6 MeV the reaction cross section (and trans. coeff.) was renormalized to values predicted by the systematics of Wellisch [We96]. The potential of Lohr (Lo74) was used for deuterons, and Mcfadden-Satchler (Mc66) for alpha particles. We followed ref. [Ch96b] in ignoring He-3 emission.

Nuclear level densities were obtained using the Ignatyuk model (Ig75), and low-lying levels were obtained after first determining the upper limit for which the experimental level information is complete.

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REFERENCES

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

[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, 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.

[Ch96b] M.B. Chadwick and P.G. Young, "Proton nuclear interactions with 12C, 14N, 16O, 31P, 40Ca for radiotherapy applications: evaluated data libraries up to 250 MeV", Los Alamos report LA-UR-96-0498.

[Ch98]. M. B. Chadwick and P. G. Young, "Model Calculations of n,p + 31P" in APT PROGRESS REPORT: 1 December 1997 - 1 January 1998, internal Los Alamos National Laboratory memo T-2-97/MS-55, 8 January 1998 from R.E. MacFarlane to L. Waters.

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

[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).

[Lo74]. J.M.Lohr and W.Haeberli, Nucl.Phys. A232,381(1974)

[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).

[Mc66]. L. McFadden and G. R. Satchler, Nucl. Phys. 84, 177 (1966).

[We96] H.P. Wellisch and D. Axen, Phys. Rev. C54, 1329(1996).

[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).

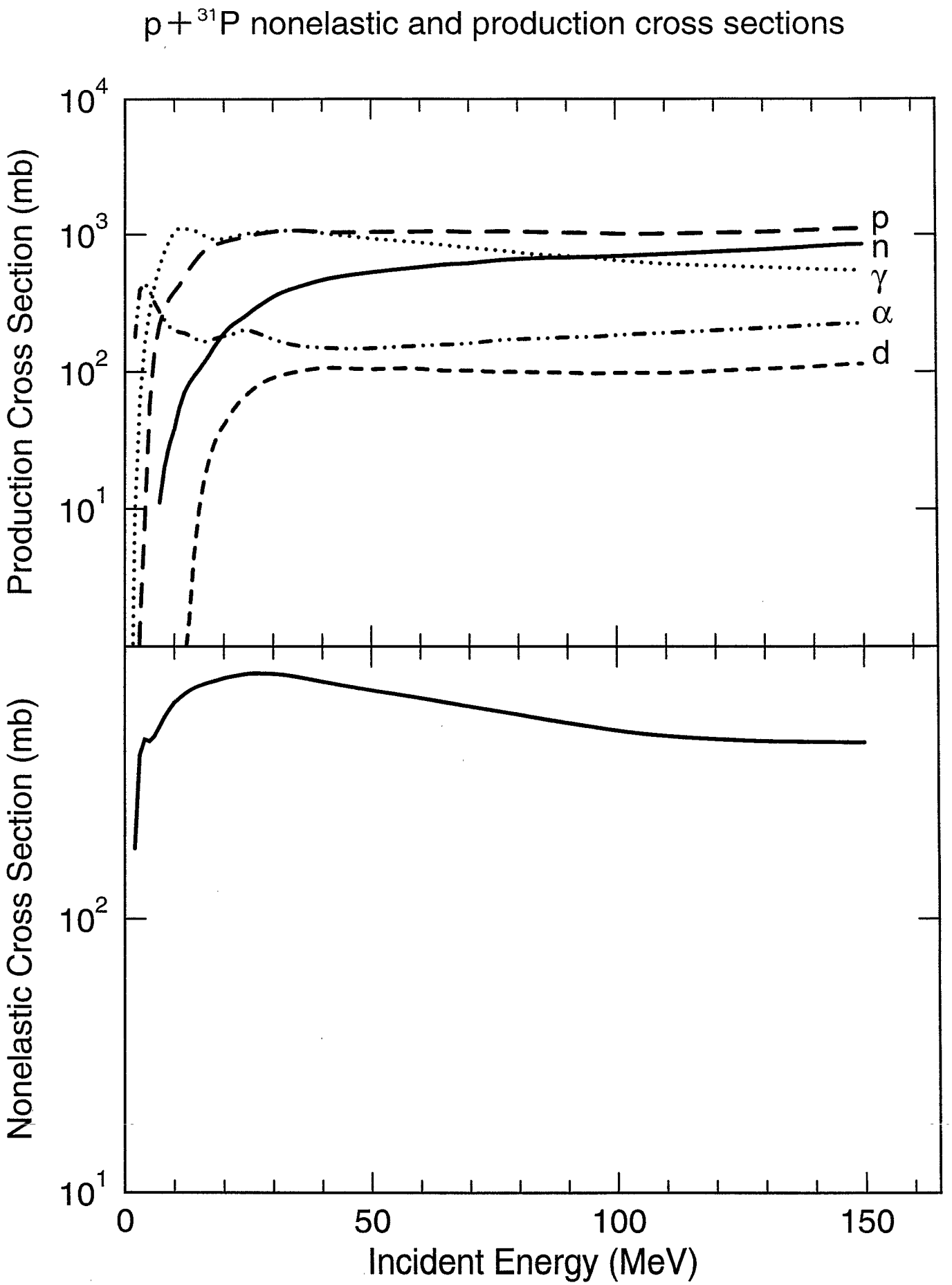
15031 = TARGET 1000Z+A (if A=0 then elemental)
1001 = PROJECTILE 1000Z+A
Nonelastic, elastic, and Production cross sections for A<5 ejectiles in barns:

Energy	nonelas	elastic	neutron	proton	deuteron	triton	helium3	alpha	gamma
1.000E+00	2.012E-03	0.000E+00	0.000E+00	1.230E-07	0.000E+00	0.000E+00	0.000E+00	2.012E-03	9.335E-05
1.307E+00	5.354E-02	0.000E+00	0.000E+00	3.273E-06	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
2.000E+00	1.802E-01	0.000E+00	0.000E+00	1.102E-05	0.000E+00	0.000E+00	0.000E+00	1.802E-01	8.359E-03
3.000E+00	3.960E-01	0.000E+00	0.000E+00	1.314E-03	0.000E+00	0.000E+00	0.000E+00	3.946E-01	6.159E-02
4.000E+00	4.517E-01	0.000E+00	0.000E+00	7.791E-03	0.000E+00	0.000E+00	0.000E+00	4.438E-01	1.612E-01
5.000E+00	4.454E-01	0.000E+00	0.000E+00	5.818E-02	0.000E+00	0.000E+00	0.000E+00	3.872E-01	2.795E-01
6.000E+00	4.655E-01	0.000E+00	0.000E+00	1.487E-01	0.000E+00	0.000E+00	0.000E+00	3.168E-01	4.330E-01
7.000E+00	5.057E-01	0.000E+00	1.111E-02	2.222E-01	0.000E+00	0.000E+00	0.000E+00	2.723E-01	5.865E-01
8.000E+00	5.467E-01	0.000E+00	2.019E-02	2.900E-01	0.000E+00	0.000E+00	0.000E+00	2.365E-01	7.504E-01
9.000E+00	5.849E-01	0.000E+00	2.944E-02	3.429E-01	0.000E+00	0.000E+00	0.000E+00	2.126E-01	9.048E-01
1.000E+01	6.196E-01	0.000E+00	3.847E-02	3.846E-01	0.000E+00	0.000E+00	0.000E+00	2.011E-01	1.047E+00
1.100E+01	6.425E-01	0.000E+00	5.487E-02	4.269E-01	2.318E-08	0.000E+00	0.000E+00	1.948E-01	1.109E+00
1.200E+01	6.659E-01	0.000E+00	7.047E-02	4.907E-01	1.212E-04	0.000E+00	0.000E+00	1.922E-01	1.103E+00
1.300E+01	6.860E-01	0.000E+00	8.289E-02	5.586E-01	1.552E-03	0.000E+00	0.000E+00	1.847E-01	1.084E+00
1.400E+01	7.035E-01	0.000E+00	9.350E-02	6.257E-01	4.688E-03	0.000E+00	0.000E+00	1.762E-01	1.070E+00
1.500E+01	7.164E-01	0.000E+00	1.036E-01	6.932E-01	9.820E-03	0.000E+00	0.000E+00	1.686E-01	1.033E+00
1.600E+01	7.281E-01	0.000E+00	1.170E-01	7.525E-01	1.601E-02	0.000E+00	0.000E+00	1.659E-01	9.822E-01
1.700E+01	7.381E-01	0.000E+00	1.322E-01	8.004E-01	2.256E-02	0.000E+00	0.000E+00	1.690E-01	9.370E-01
1.800E+01	7.470E-01	0.000E+00	1.512E-01	8.321E-01	2.945E-02	0.000E+00	0.000E+00	1.735E-01	9.174E-01
1.900E+01	7.562E-01	0.000E+00	1.701E-01	8.554E-01	3.600E-02	0.000E+00	0.000E+00	1.787E-01	9.230E-01
2.000E+01	7.662E-01	0.000E+00	1.906E-01	8.788E-01	4.074E-02	0.000E+00	0.000E+00	1.829E-01	9.259E-01
2.200E+01	7.791E-01	0.000E+00	2.226E-01	9.162E-01	5.325E-02	0.000E+00	0.000E+00	1.897E-01	9.647E-01
2.400E+01	7.914E-01	0.000E+00	2.483E-01	9.560E-01	6.451E-02	0.000E+00	0.000E+00	2.012E-01	1.001E+00
2.600E+01	7.984E-01	0.000E+00	2.826E-01	9.948E-01	7.481E-02	0.000E+00	0.000E+00	1.962E-01	1.027E+00
2.800E+01	7.972E-01	0.000E+00	3.159E-01	1.023E+00	8.386E-02	0.000E+00	0.000E+00	1.847E-01	1.044E+00
3.000E+01	7.946E-01	0.000E+00	3.510E-01	1.047E+00	9.038E-02	0.000E+00	0.000E+00	1.731E-01	1.055E+00
3.500E+01	7.731E-01	0.000E+00	4.139E-01	1.066E+00	1.003E-01	0.000E+00	0.000E+00	1.550E-01	1.066E+00
4.000E+01	7.431E-01	0.000E+00	4.653E-01	1.043E+00	1.063E-01	0.000E+00	0.000E+00	1.501E-01	1.023E+00
4.500E+01	7.145E-01	0.000E+00	5.010E-01	1.037E+00	1.058E-01	0.000E+00	0.000E+00	1.472E-01	9.780E-01
5.000E+01	6.883E-01	0.000E+00	5.286E-01	1.043E+00	1.042E-01	0.000E+00	0.000E+00	1.484E-01	9.334E-01
5.500E+01	6.656E-01	0.000E+00	5.546E-01	1.048E+00	1.057E-01	0.000E+00	0.000E+00	1.517E-01	9.006E-01
6.000E+01	6.434E-01	0.000E+00	5.781E-01	1.050E+00	1.049E-01	0.000E+00	0.000E+00	1.547E-01	8.702E-01
6.500E+01	6.212E-01	0.000E+00	6.036E-01	1.057E+00	1.018E-01	0.000E+00	0.000E+00	1.579E-01	8.332E-01
7.000E+01	5.993E-01	0.000E+00	6.185E-01	1.043E+00	1.020E-01	0.000E+00	0.000E+00	1.608E-01	7.984E-01
7.500E+01	5.788E-01	0.000E+00	6.448E-01	1.052E+00	9.976E-02	0.000E+00	0.000E+00	1.685E-01	7.697E-01
8.000E+01	5.584E-01	0.000E+00	6.626E-01	1.048E+00	9.954E-02	0.000E+00	0.000E+00	1.729E-01	7.368E-01
8.500E+01	5.381E-01	0.000E+00	6.729E-01	1.039E+00	9.862E-02	0.000E+00	0.000E+00	1.750E-01	7.084E-01
9.000E+01	5.205E-01	0.000E+00	6.794E-01	1.031E+00	9.811E-02	0.000E+00	0.000E+00	1.784E-01	6.947E-01
9.500E+01	5.040E-01	0.000E+00	6.854E-01	1.025E+00	9.694E-02	0.000E+00	0.000E+00	1.799E-01	6.756E-01
1.000E+02	4.879E-01	0.000E+00	6.948E-01	1.013E+00	9.780E-02	0.000E+00	0.000E+00	1.848E-01	6.500E-01
1.100E+02	4.658E-01	0.000E+00	7.186E-01	1.015E+00	9.790E-02	0.000E+00	0.000E+00	1.923E-01	6.115E-01
1.200E+02	4.534E-01	0.000E+00	7.453E-01	1.028E+00	1.009E-01	0.000E+00	0.000E+00	2.000E-01	5.912E-01
1.300E+02	4.457E-01	0.000E+00	7.749E-01	1.045E+00	1.048E-01	0.000E+00	0.000E+00	2.080E-01	5.765E-01
1.400E+02	4.428E-01	0.000E+00	8.147E-01	1.078E+00	1.086E-01	0.000E+00	0.000E+00	2.176E-01	5.591E-01
1.500E+02	4.406E-01	0.000E+00	8.475E-01	1.105E+00	1.137E-01	0.000E+00	0.000E+00	2.243E-01	5.495E-01

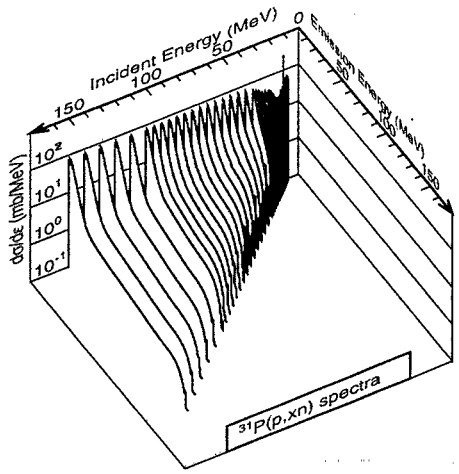
15031 = TARGET 1000Z+A (if A=0 then elemental)
1001 = PROJECTILE 1000Z+A
Aver. lab emission energies for A<5 ejectiles in MeV:

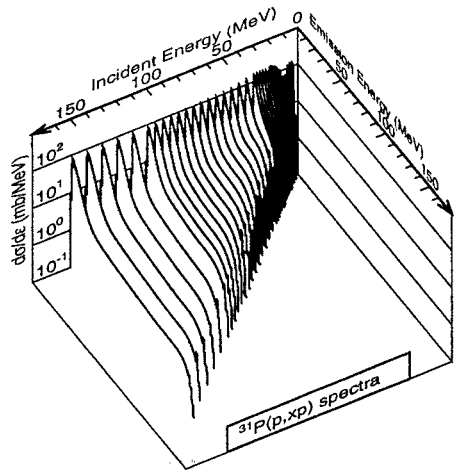
Energy	neutron	proton	deuteron	triton	helium3	alpha	gamma
1.000E+00	0.000E+00	9.935E-04	0.000E+00	0.000E+00	0.000E+00	3.974E-03	5.000E-12
1.307E+00	0.000E+00	1.299E-03	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
2.000E+00	0.000E+00	7.360E-01	0.000E+00	0.000E+00	0.000E+00	3.262E+00	1.782E+00
3.000E+00	0.000E+00	1.692E+00	0.000E+00	0.000E+00	0.000E+00	3.991E+00	1.745E+00
4.000E+00	0.000E+00	2.301E+00	0.000E+00	0.000E+00	0.000E+00	4.593E+00	1.739E+00
5.000E+00	0.000E+00	2.818E+00	0.000E+00	0.000E+00	0.000E+00	5.142E+00	1.778E+00
6.000E+00	0.000E+00	3.160E+00	0.000E+00	0.000E+00	0.000E+00	5.607E+00	1.947E+00
7.000E+00	4.799E-01	3.458E+00	0.000E+00	0.000E+00	0.000E+00	6.075E+00	2.104E+00
8.000E+00	9.497E-01	3.787E+00	0.000E+00	0.000E+00	0.000E+00	6.448E+00	2.268E+00
9.000E+00	1.457E+00	4.143E+00	0.000E+00	0.000E+00	0.000E+00	6.638E+00	2.450E+00
1.000E+01	1.824E+00	4.448E+00	0.000E+00	0.000E+00	0.000E+00	6.777E+00	2.627E+00
1.100E+01	1.898E+00	4.512E+00	4.799E-01	0.000E+00	0.000E+00	6.892E+00	2.732E+00
1.200E+01	2.148E+00	4.425E+00	1.381E+00	0.000E+00	0.000E+00	7.051E+00	2.802E+00
1.300E+01	2.454E+00	4.481E+00	2.137E+00	0.000E+00	0.000E+00	7.248E+00	2.871E+00
1.400E+01	2.757E+00	4.542E+00	2.774E+00	0.000E+00	0.000E+00	7.422E+00	2.929E+00
1.500E+01	3.020E+00	4.579E+00	3.423E+00	0.000E+00	0.000E+00	7.610E+00	2.935E+00
1.600E+01	3.189E+00	4.656E+00	4.040E+00	0.000E+00	0.000E+00	7.652E+00	2.910E+00
1.700E+01	3.246E+00	4.765E+00	4.642E+00	0.000E+00	0.000E+00	7.558E+00	2.814E+00
1.800E+01	3.328E+00	4.898E+00	5.169E+00	0.000E+00	0.000E+00	7.477E+00	2.677E+00
1.900E+01	3.452E+00	5.027E+00	5.690E+00	0.000E+00	0.000E+00	7.439E+00	2.538E+00
2.000E+01	3.647E+00	5.248E+00	6.275E+00	0.000E+00	0.000E+00	7.396E+00	2.333E+00

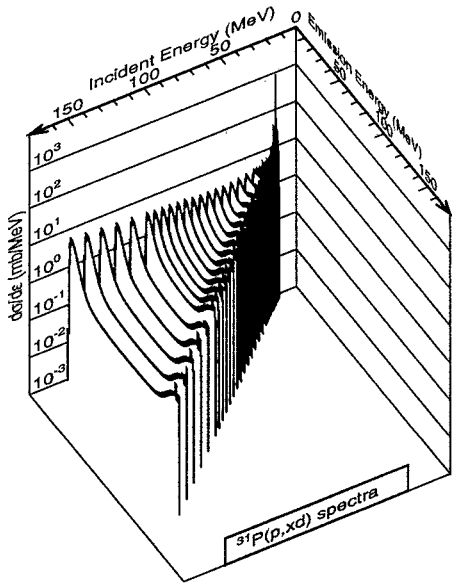
2.200E+01	3.980E+00	5.651E+00	7.336E+00	0.000E+00	0.000E+00	7.473E+00	2.208E+00
2.400E+01	4.391E+00	5.948E+00	8.344E+00	0.000E+00	0.000E+00	7.591E+00	2.175E+00
2.600E+01	4.683E+00	6.336E+00	9.370E+00	0.000E+00	0.000E+00	7.868E+00	2.196E+00
2.800E+01	4.946E+00	6.764E+00	1.040E+01	0.000E+00	0.000E+00	8.165E+00	2.209E+00
3.000E+01	5.211E+00	7.194E+00	1.130E+01	0.000E+00	0.000E+00	8.451E+00	2.212E+00
3.500E+01	5.982E+00	8.366E+00	1.401E+01	0.000E+00	0.000E+00	8.806E+00	2.178E+00
4.000E+01	6.691E+00	9.703E+00	1.692E+01	0.000E+00	0.000E+00	9.029E+00	2.148E+00
4.500E+01	7.432E+00	1.097E+01	1.967E+01	0.000E+00	0.000E+00	9.214E+00	2.162E+00
5.000E+01	8.176E+00	1.201E+01	2.227E+01	0.000E+00	0.000E+00	9.349E+00	2.164E+00
5.500E+01	8.853E+00	1.300E+01	2.468E+01	0.000E+00	0.000E+00	9.485E+00	2.179E+00
6.000E+01	9.495E+00	1.401E+01	2.707E+01	0.000E+00	0.000E+00	9.556E+00	2.178E+00
6.500E+01	1.009E+01	1.487E+01	2.891E+01	0.000E+00	0.000E+00	9.640E+00	2.158E+00
7.000E+01	1.069E+01	1.581E+01	3.129E+01	0.000E+00	0.000E+00	9.670E+00	2.101E+00
7.500E+01	1.108E+01	1.645E+01	3.219E+01	0.000E+00	0.000E+00	9.715E+00	2.090E+00
8.000E+01	1.159E+01	1.711E+01	3.405E+01	0.000E+00	0.000E+00	9.777E+00	2.080E+00
8.500E+01	1.209E+01	1.784E+01	3.570E+01	0.000E+00	0.000E+00	9.838E+00	2.064E+00
9.000E+01	1.265E+01	1.852E+01	3.723E+01	0.000E+00	0.000E+00	9.867E+00	2.057E+00
9.500E+01	1.322E+01	1.922E+01	3.823E+01	0.000E+00	0.000E+00	9.946E+00	2.069E+00
1.000E+02	1.364E+01	1.989E+01	3.932E+01	0.000E+00	0.000E+00	9.968E+00	2.058E+00
1.100E+02	1.463E+01	2.115E+01	4.125E+01	0.000E+00	0.000E+00	1.010E+01	2.054E+00
1.200E+02	1.567E+01	2.236E+01	4.320E+01	0.000E+00	0.000E+00	1.025E+01	2.056E+00
1.300E+02	1.666E+01	2.364E+01	4.414E+01	0.000E+00	0.000E+00	1.039E+01	2.086E+00
1.400E+02	1.758E+01	2.482E+01	4.485E+01	0.000E+00	0.000E+00	1.055E+01	2.096E+00
1.500E+02	1.853E+01	2.601E+01	4.602E+01	0.000E+00	0.000E+00	1.071E+01	2.108E+00

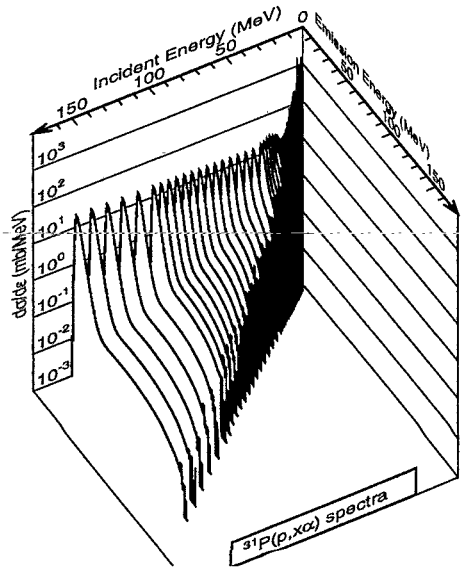

p + 31P nonelastic and production cross sections
Production Cross Section (mb)
10^4
10^3
10^2
10^1
p
n
γ
α
d
Nonelastic Cross Section (mb)
10^2
10^1
0
50
100
150
Incident Energy (MeV)

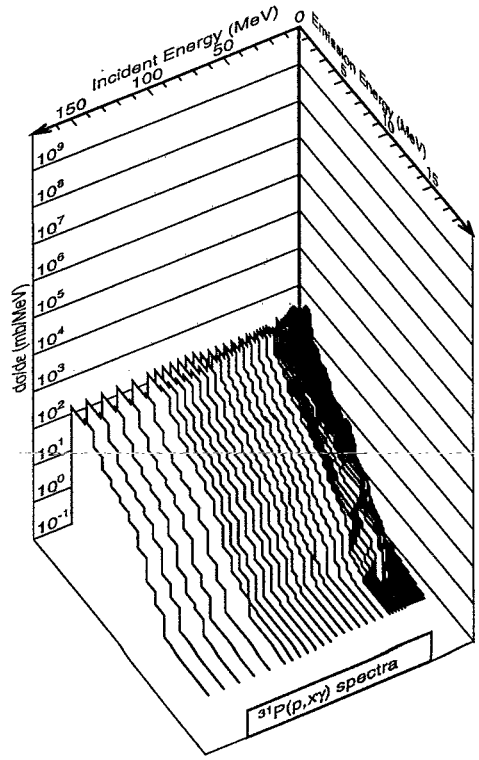
p + ^{31}P angle-integrated emission spectra



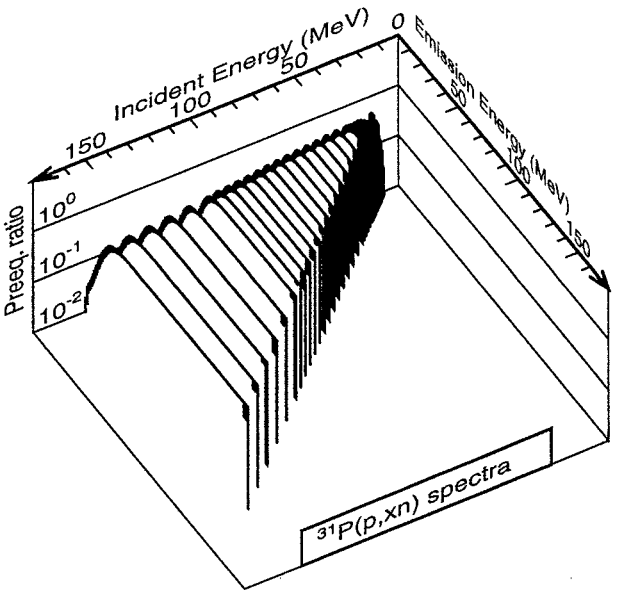


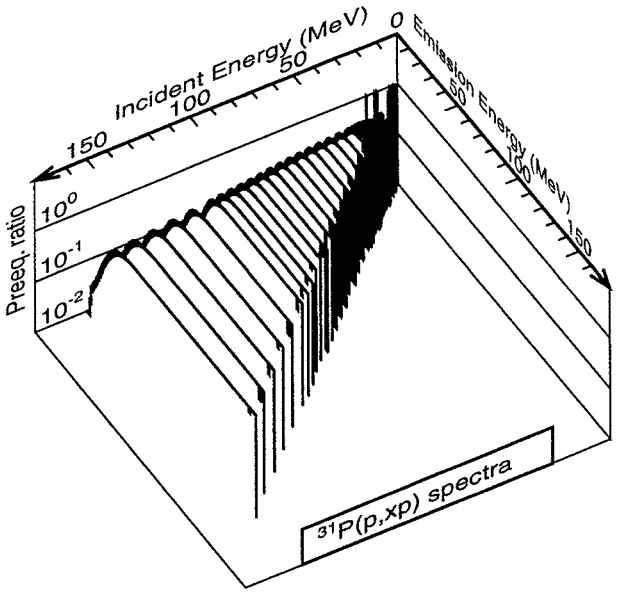


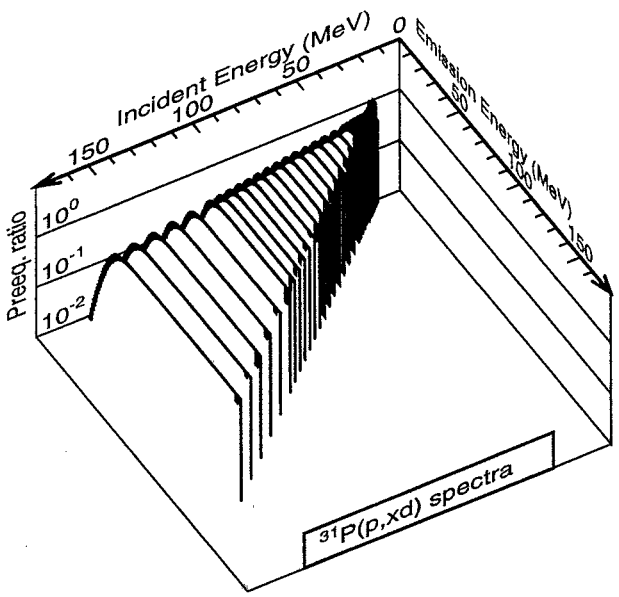


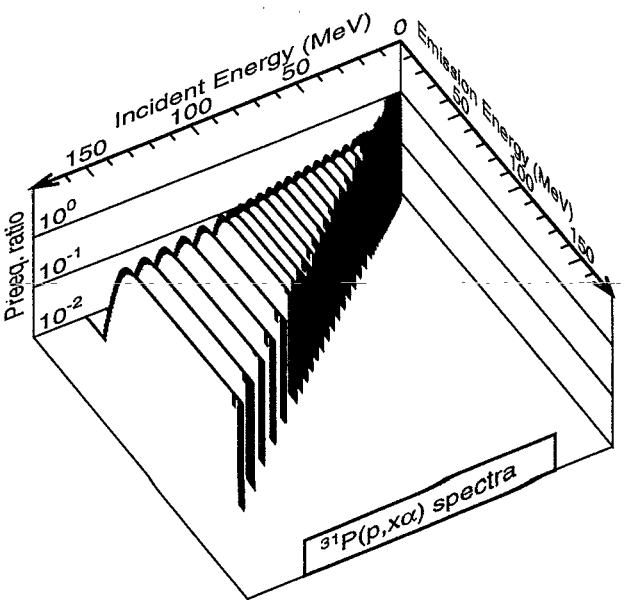


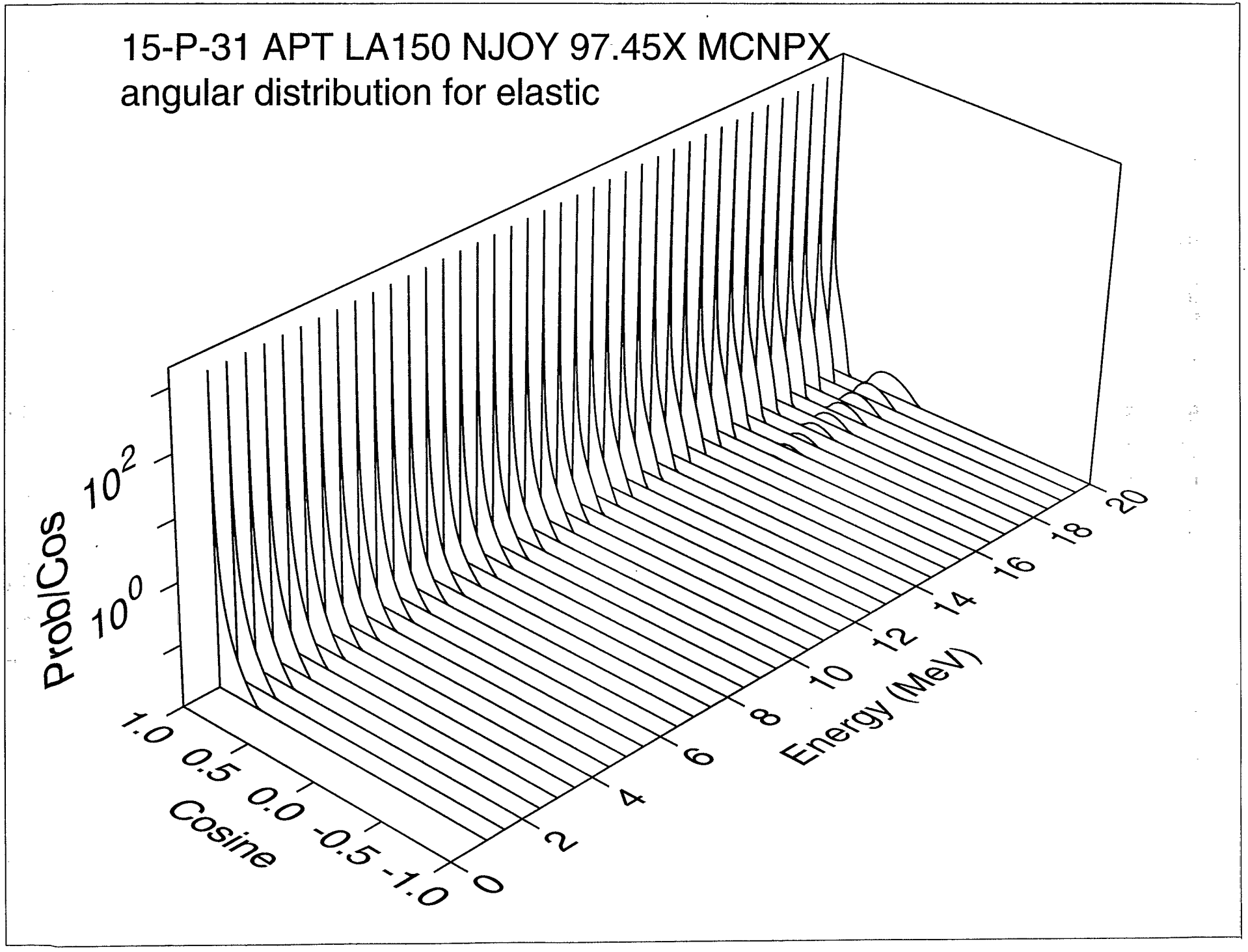
p + ^{31}P Kalbach preequilibrium ratios

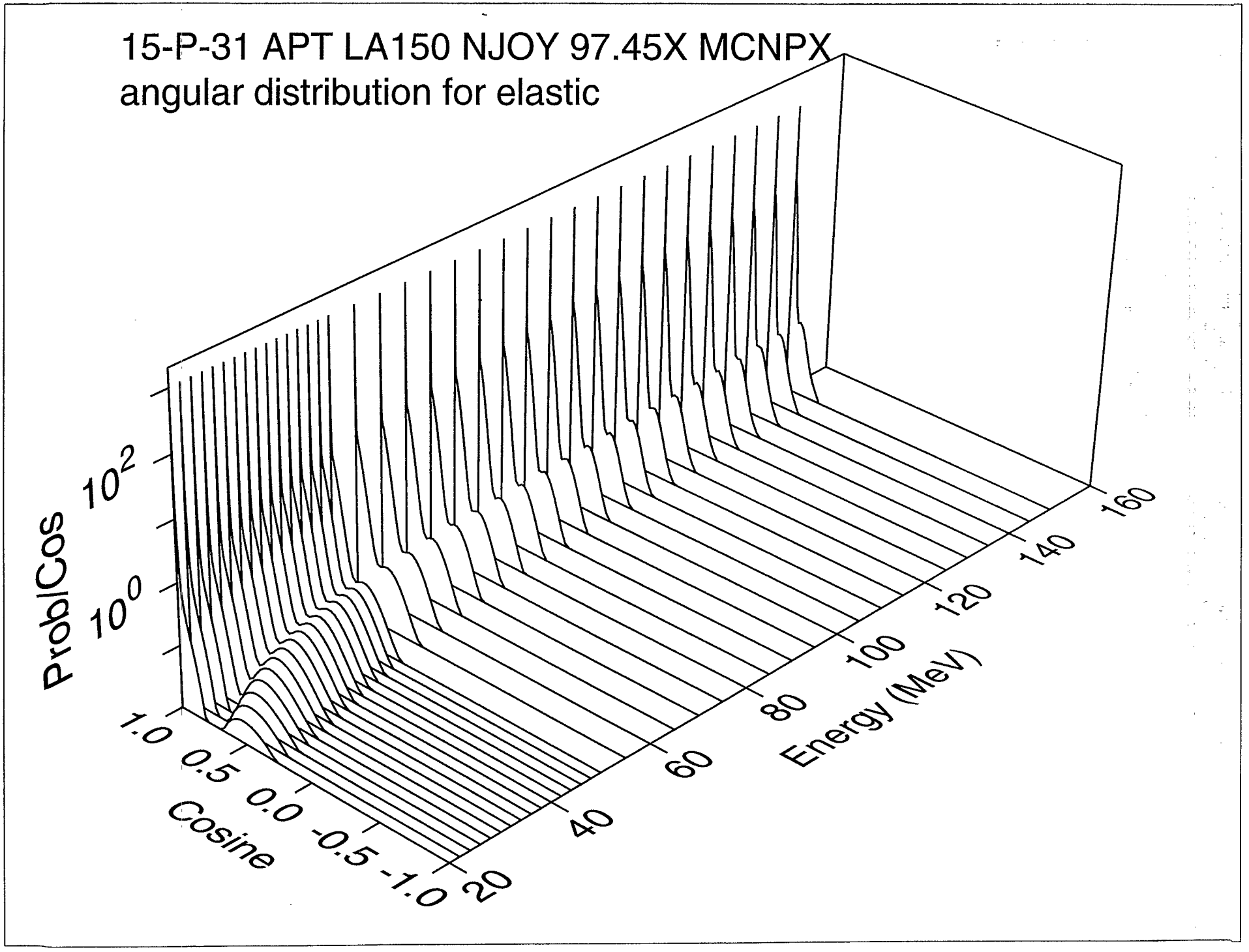


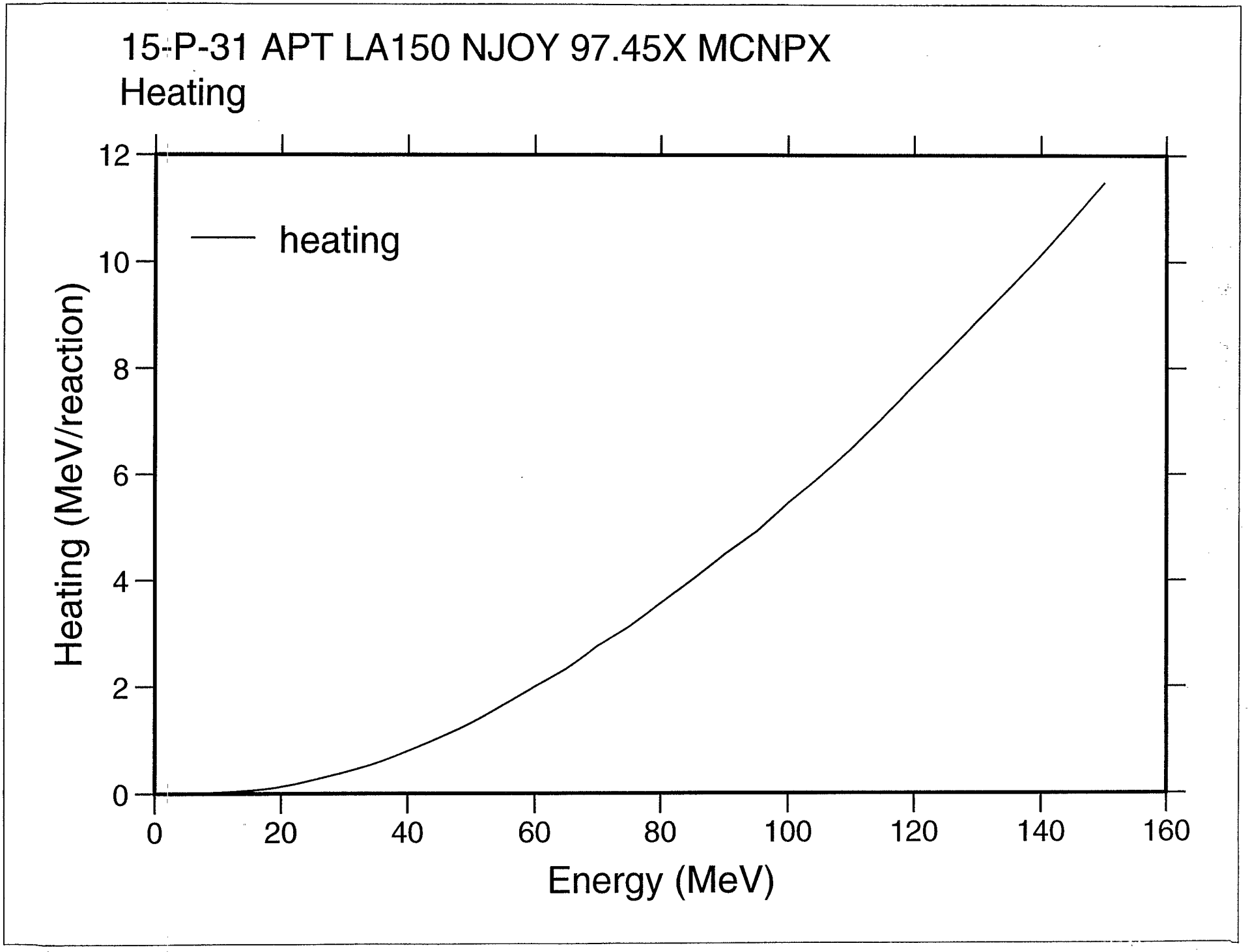







15-P-31 APT LA150 NJOY 97.45X MCNPX
angular distribution for elastic
Prob/Cos
10^2
10^0
1.0
0.5
0.0
-0.5
-1.0
Cosine
0
2
4
6
8
10
12
14
16
18
20
Energy (MeV)


15-P-31 APT LA150 NJOY 97.45X MCNPX
angular distribution for elastic
Prob/Cos
10^2
10^0
1.0
0.5
0.0
-0.5
-1.0
Cosine
20
40
60
80
100
120
140
160
Energy (MeV)


15-P-31 APT LA150 NJOY 97.45X MCNPX
Heating
heating
Heating (MeV/reaction)
Energy (MeV)
0
2
4
6
8
10
12
0
20
40
60
80
100
120
140
160