EVALUATION OF n + 31P CROSS SECTIONS FOR THE ENERGY RANGE 1.0E-11 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 1.0E-11 to 150 MeV. The discussion here is divided into the region below and above 20 MeV.

INCIDENT NEUTRON ENERGIES < 20 MeV

Below 20 MeV the evaluation is based completely on the ENDF/B-VI (Release 1) evaluation by R. Howerton (1977).

INCIDENT NEUTRON ENERGIES > 20 MeV

The ENDF/B-VI Release 2 evaluation extends to 20 MeV and includes cross sections and energy-angle data for all significant reactions. The present evaluation utilizes a more compact composite reaction spectrum representation above 20 MeV in order to reduce the length of the file. No essential data for applications is lost with this representation.

The evaluation above 20 MeV 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 En = 20 MeV are:

MF=3	MT=	1	Total Cross Section
	MT=	2	Elastic Scattering Cross Section
	MT=	3	Nonelastic Cross Section
	MT=	5	Sum of Binary (n,n') and (n,x) Reactions
MF=4	MT=	2	Elastic Angular Distributions
MF=6	MT=	5	Production Cross Sections and Energy-Angle Distributions for Emission Neutrons, Protons, Deuterons, Tritons, 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 neutron 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.

The total cross section was evaluated in the following way. The only measurement above 20 MeV is that of Deconninck et al. (Di61), who measure 2030 +/- 60 mb at 28.4 MeV. We took the evaluated total cross section data from our high-energy n+Si28 evaluation (based primarily on Finlay's 1993 (Fi93) total cross section data), and scaled the values to agree with the Deconninck measurement (a 5% increase). Note that this scaling is approximately consistent with an A**{2/3} dependence in the total cross section (which would give a 7% difference). Our evaluated total cross section at 20 MeV now exceeds the ENDF/B-VI value at 20 MeV by 15%; however, as explained above, arguments exist for our larger value.

We also note that our evaluated nonelastic cross section, which results from optical model calculations, is approximately 20% higher than the ENDF/B-VI value at 20 MeV. No experimental data are available to constrain the evaluation in this energy range. We do note, however, that systematics embodied in the neutron nonelastic cross section parameterization from NASA (Tr97) also supports our higher value, giving a prediction of 959 mb at 20 MeV, a value approximately 3% higher than our evaluated result.

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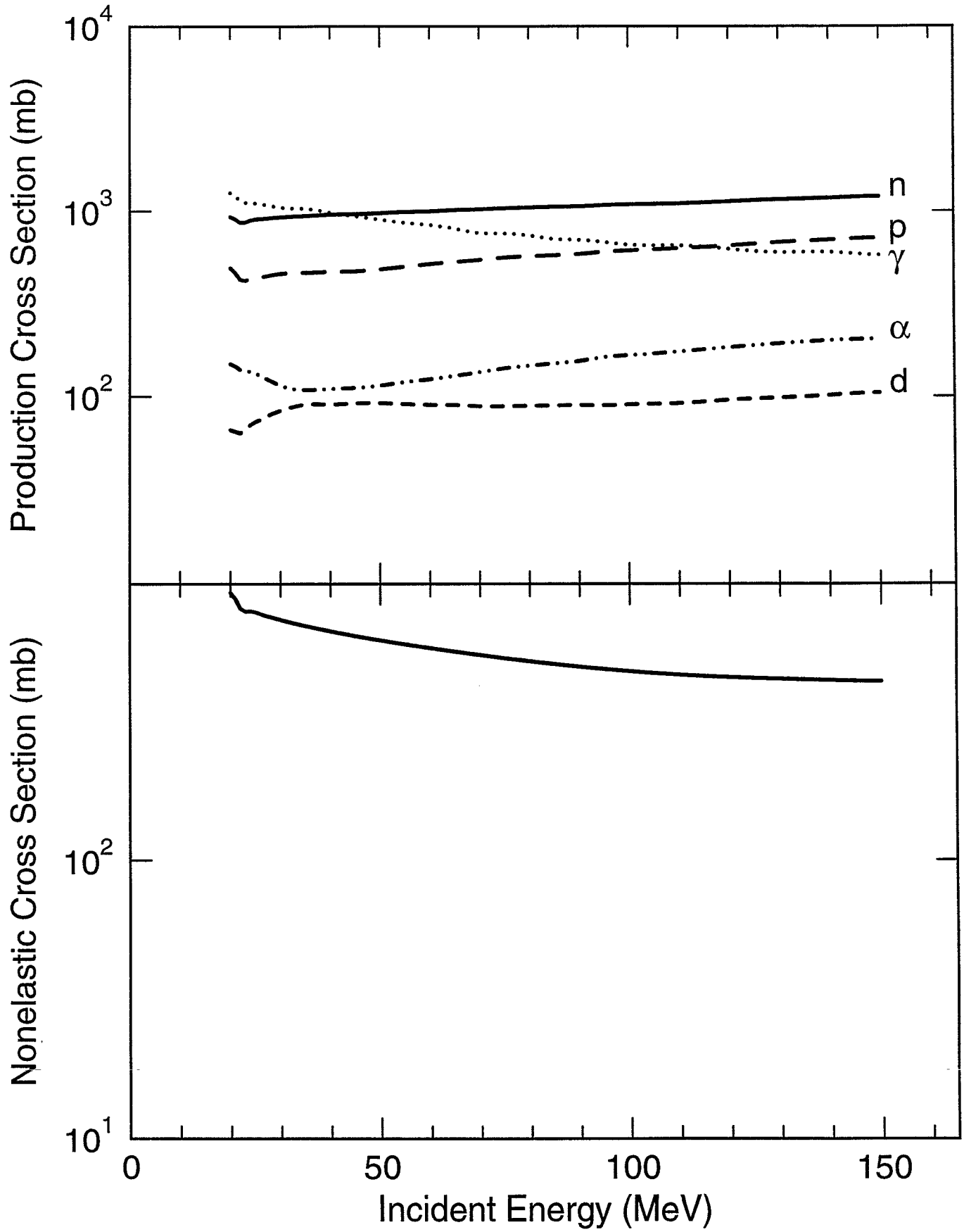
15031 = TARGET 1000Z+A (if A=0 then elemental)
1 = PROJECTILE 1000Z+A
Nonelastic, elastic, and Production cross sections for A<5 ejectiles in barns:

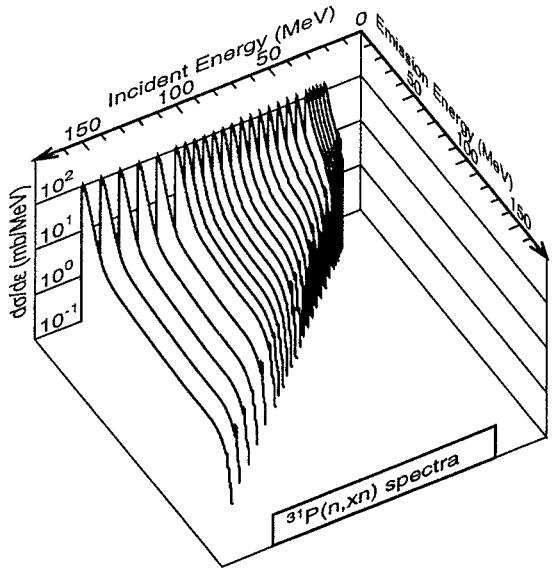
Energy	nonelas	elastic	neutron	proton	deuteron	triton	helium3	alpha	gamma
2.000E+01	9.308E-01	9.995E-01	9.314E-01	4.931E-01	6.590E-02	0.000E+00	0.000E+00	1.498E-01	1.253E+00
2.200E+01	8.150E-01	1.157E+00	8.671E-01	4.267E-01	6.341E-02	0.000E+00	0.000E+00	1.391E-01	1.138E+00
2.400E+01	7.954E-01	1.204E+00	8.912E-01	4.334E-01	7.014E-02	0.000E+00	0.000E+00	1.360E-01	1.107E+00
2.600E+01	7.753E-01	1.244E+00	9.078E-01	4.413E-01	7.480E-02	0.000E+00	0.000E+00	1.290E-01	1.091E+00
2.800E+01	7.557E-01	1.273E+00	9.184E-01	4.513E-01	7.978E-02	0.000E+00	0.000E+00	1.214E-01	1.069E+00
3.000E+01	7.378E-01	1.294E+00	9.283E-01	4.603E-01	8.364E-02	0.000E+00	0.000E+00	1.145E-01	1.044E+00
3.500E+01	7.006E-01	1.322E+00	9.425E-01	4.661E-01	9.036E-02	0.000E+00	0.000E+00	1.083E-01	1.029E+00
4.000E+01	6.701E-01	1.314E+00	9.591E-01	4.717E-01	9.063E-02	0.000E+00	0.000E+00	1.099E-01	9.814E-01
4.500E+01	6.439E-01	1.279E+00	9.649E-01	4.751E-01	9.188E-02	0.000E+00	0.000E+00	1.114E-01	9.401E-01
5.000E+01	6.210E-01	1.231E+00	9.767E-01	4.863E-01	9.207E-02	0.000E+00	0.000E+00	1.145E-01	9.011E-01
5.500E+01	6.004E-01	1.168E+00	9.894E-01	5.023E-01	9.087E-02	0.000E+00	0.000E+00	1.195E-01	8.654E-01
6.000E+01	5.818E-01	1.097E+00	9.973E-01	5.186E-01	9.009E-02	0.000E+00	0.000E+00	1.237E-01	8.417E-01
6.500E+01	5.648E-01	1.028E+00	1.013E+00	5.324E-01	8.976E-02	0.000E+00	0.000E+00	1.290E-01	8.041E-01
7.000E+01	5.492E-01	9.636E-01	1.024E+00	5.465E-01	8.841E-02	0.000E+00	0.000E+00	1.349E-01	7.613E-01
7.500E+01	5.349E-01	8.940E-01	1.037E+00	5.618E-01	8.841E-02	0.000E+00	0.000E+00	1.418E-01	7.564E-01
8.000E+01	5.217E-01	8.305E-01	1.046E+00	5.708E-01	8.898E-02	0.000E+00	0.000E+00	1.464E-01	7.373E-01
8.500E+01	5.098E-01	7.670E-01	1.056E+00	5.778E-01	8.926E-02	0.000E+00	0.000E+00	1.506E-01	7.070E-01
9.000E+01	4.989E-01	7.149E-01	1.062E+00	5.865E-01	8.980E-02	0.000E+00	0.000E+00	1.550E-01	6.984E-01
9.500E+01	4.891E-01	6.628E-01	1.078E+00	6.020E-01	8.944E-02	0.000E+00	0.000E+00	1.626E-01	6.795E-01
1.000E+02	4.804E-01	6.159E-01	1.087E+00	6.126E-01	9.050E-02	0.000E+00	0.000E+00	1.665E-01	6.570E-01
1.100E+02	4.662E-01	5.368E-01	1.100E+00	6.297E-01	9.194E-02	0.000E+00	0.000E+00	1.744E-01	6.523E-01
1.200E+02	4.565E-01	4.678E-01	1.128E+00	6.507E-01	9.575E-02	0.000E+00	0.000E+00	1.840E-01	6.234E-01
1.300E+02	4.503E-01	4.089E-01	1.157E+00	6.785E-01	9.837E-02	0.000E+00	0.000E+00	1.929E-01	5.979E-01
1.400E+02	4.449E-01	3.608E-01	1.178E+00	6.987E-01	1.015E-01	0.000E+00	0.000E+00	2.007E-01	5.997E-01
1.500E+02	4.416E-01	3.222E-01	1.199E+00	7.142E-01	1.044E-01	0.000E+00	0.000E+00	2.041E-01	5.781E-01

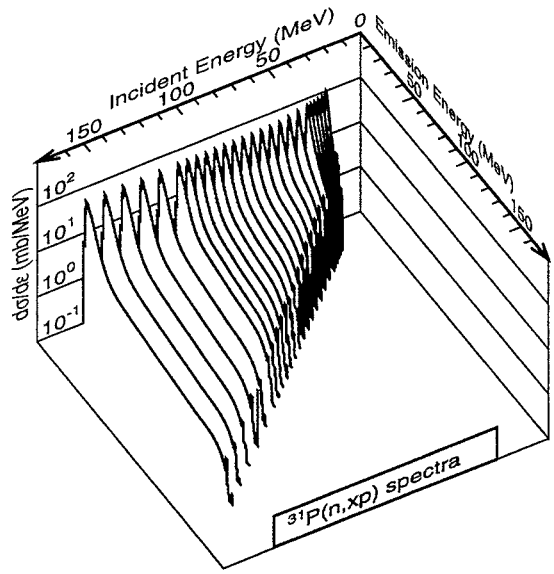
15031 = TARGET 1000Z+A (if A=0 then elemental)
1 = PROJECTILE 1000Z+A
Kerma coefficients in units of f.Gy.m^2:

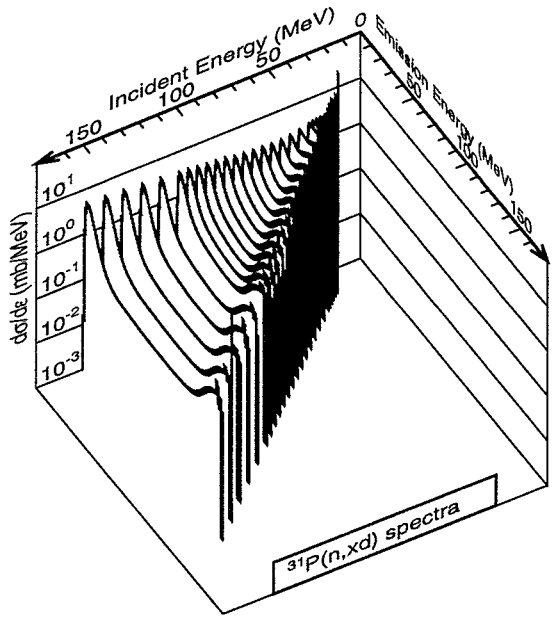
Energy	proton	deuteron	triton	helium3	alpha	non-rec	elas-rec	TOTAL
2.000E+01	6.708E-01	1.709E-01	0.000E+00	0.000E+00	2.873E-01	2.450E-01	1.260E-01	1.500E+00
2.200E+01	6.375E-01	1.854E-01	0.000E+00	0.000E+00	2.837E-01	2.311E-01	1.358E-01	1.474E+00
2.400E+01	6.980E-01	2.270E-01	0.000E+00	0.000E+00	2.919E-01	2.403E-01	1.295E-01	1.587E+00
2.600E+01	7.651E-01	2.635E-01	0.000E+00	0.000E+00	2.898E-01	2.475E-01	1.224E-01	1.688E+00
2.800E+01	8.335E-01	3.068E-01	0.000E+00	0.000E+00	2.826E-01	2.526E-01	1.151E-01	1.791E+00
3.000E+01	9.091E-01	3.473E-01	0.000E+00	0.000E+00	2.750E-01	2.568E-01	1.083E-01	1.896E+00
3.500E+01	1.098E+00	4.578E-01	0.000E+00	0.000E+00	2.700E-01	2.683E-01	9.385E-02	2.188E+00
4.000E+01	1.303E+00	5.381E-01	0.000E+00	0.000E+00	2.826E-01	2.811E-01	8.208E-02	2.487E+00
4.500E+01	1.502E+00	6.328E-01	0.000E+00	0.000E+00	2.946E-01	2.929E-01	7.248E-02	2.795E+00
5.000E+01	1.706E+00	7.144E-01	0.000E+00	0.000E+00	3.085E-01	3.033E-01	6.471E-02	3.096E+00
5.500E+01	1.911E+00	7.679E-01	0.000E+00	0.000E+00	3.271E-01	3.096E-01	5.799E-02	3.373E+00
6.000E+01	2.115E+00	8.270E-01	0.000E+00	0.000E+00	3.432E-01	3.175E-01	5.204E-02	3.655E+00
6.500E+01	2.309E+00	8.847E-01	0.000E+00	0.000E+00	3.619E-01	3.249E-01	4.707E-02	3.928E+00
7.000E+01	2.504E+00	9.189E-01	0.000E+00	0.000E+00	3.807E-01	3.313E-01	4.292E-02	4.178E+00
7.500E+01	2.685E+00	9.544E-01	0.000E+00	0.000E+00	4.033E-01	3.386E-01	3.895E-02	4.420E+00
8.000E+01	2.870E+00	1.012E+00	0.000E+00	0.000E+00	4.207E-01	3.419E-01	3.554E-02	4.680E+00
8.500E+01	3.043E+00	1.063E+00	0.000E+00	0.000E+00	4.374E-01	3.455E-01	3.235E-02	4.921E+00
9.000E+01	3.216E+00	1.114E+00	0.000E+00	0.000E+00	4.526E-01	3.486E-01	2.981E-02	5.160E+00
9.500E+01	3.387E+00	1.114E+00	0.000E+00	0.000E+00	4.778E-01	3.510E-01	2.737E-02	5.357E+00
1.000E+02	3.565E+00	1.166E+00	0.000E+00	0.000E+00	4.929E-01	3.543E-01	2.522E-02	5.603E+00
1.100E+02	3.923E+00	1.235E+00	0.000E+00	0.000E+00	5.246E-01	3.611E-01	2.171E-02	6.065E+00
1.200E+02	4.288E+00	1.339E+00	0.000E+00	0.000E+00	5.637E-01	3.699E-01	1.873E-02	6.579E+00
1.300E+02	4.688E+00	1.397E+00	0.000E+00	0.000E+00	6.003E-01	3.860E-01	1.624E-02	7.088E+00
1.400E+02	5.085E+00	1.465E+00	0.000E+00	0.000E+00	6.337E-01	4.096E-01	1.421E-02	7.607E+00
1.500E+02	5.512E+00	1.575E+00	0.000E+00	0.000E+00	6.551E-01	4.285E-01	1.258E-02	8.183E+00

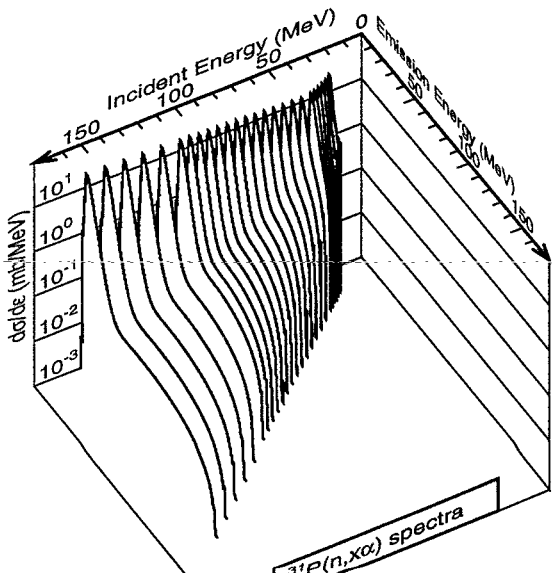

n + 31P nonelastic and production cross sections
Production Cross Section (mb)
Nonelastic Cross Section (mb)
Incident Energy (MeV)
n
p
γ
α
d
10^4
10^3
10^2
10^2
10^1
0
50
100
150

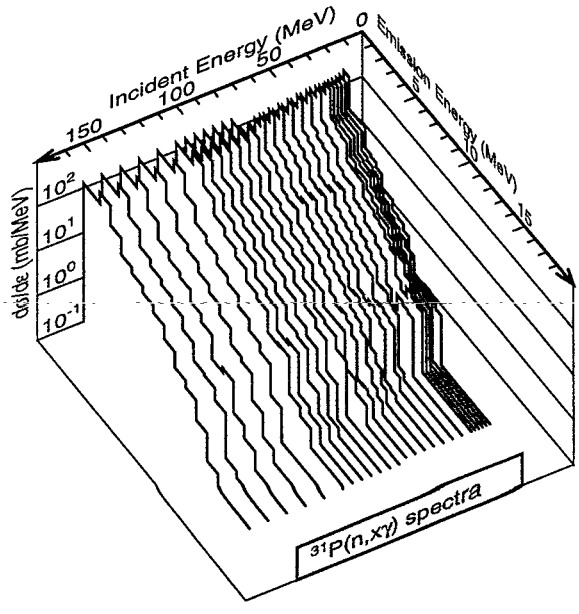
n + ^{31}P angle-integrated emission spectra



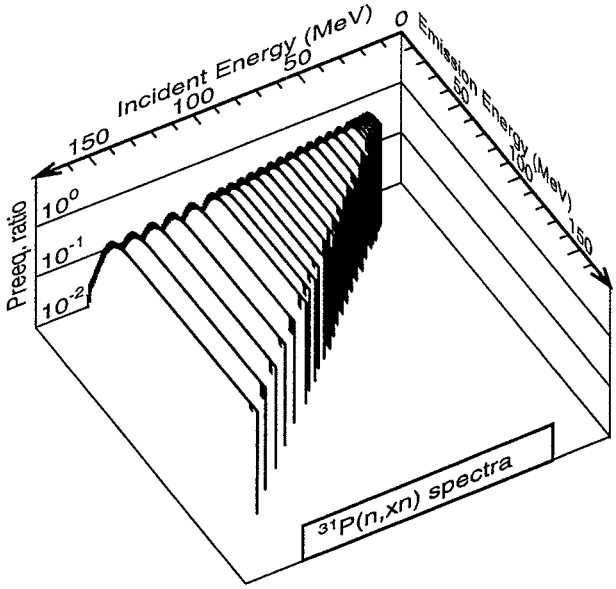


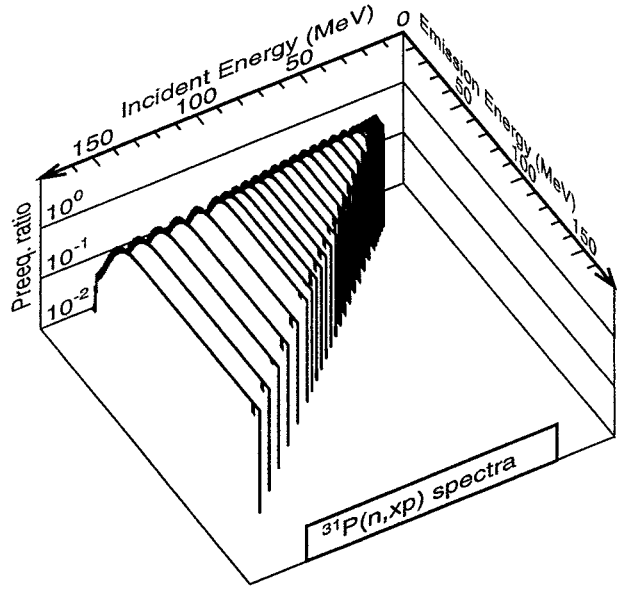


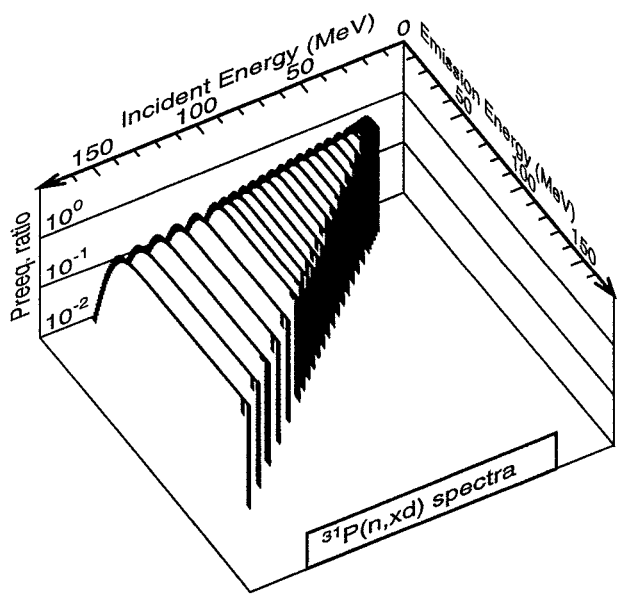


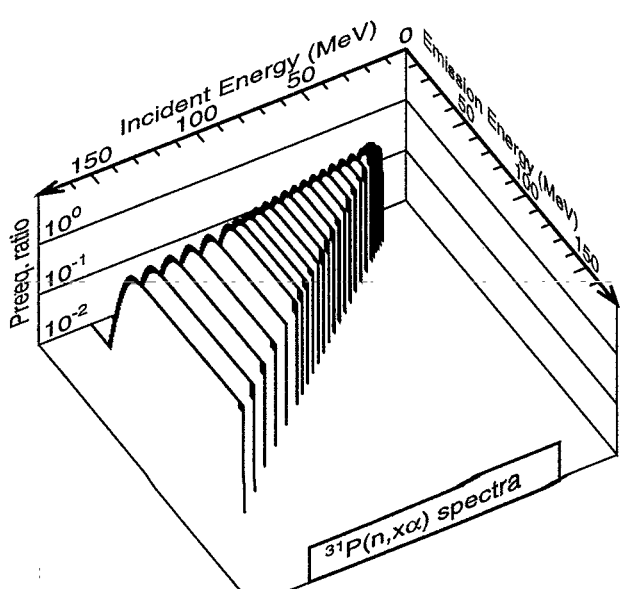


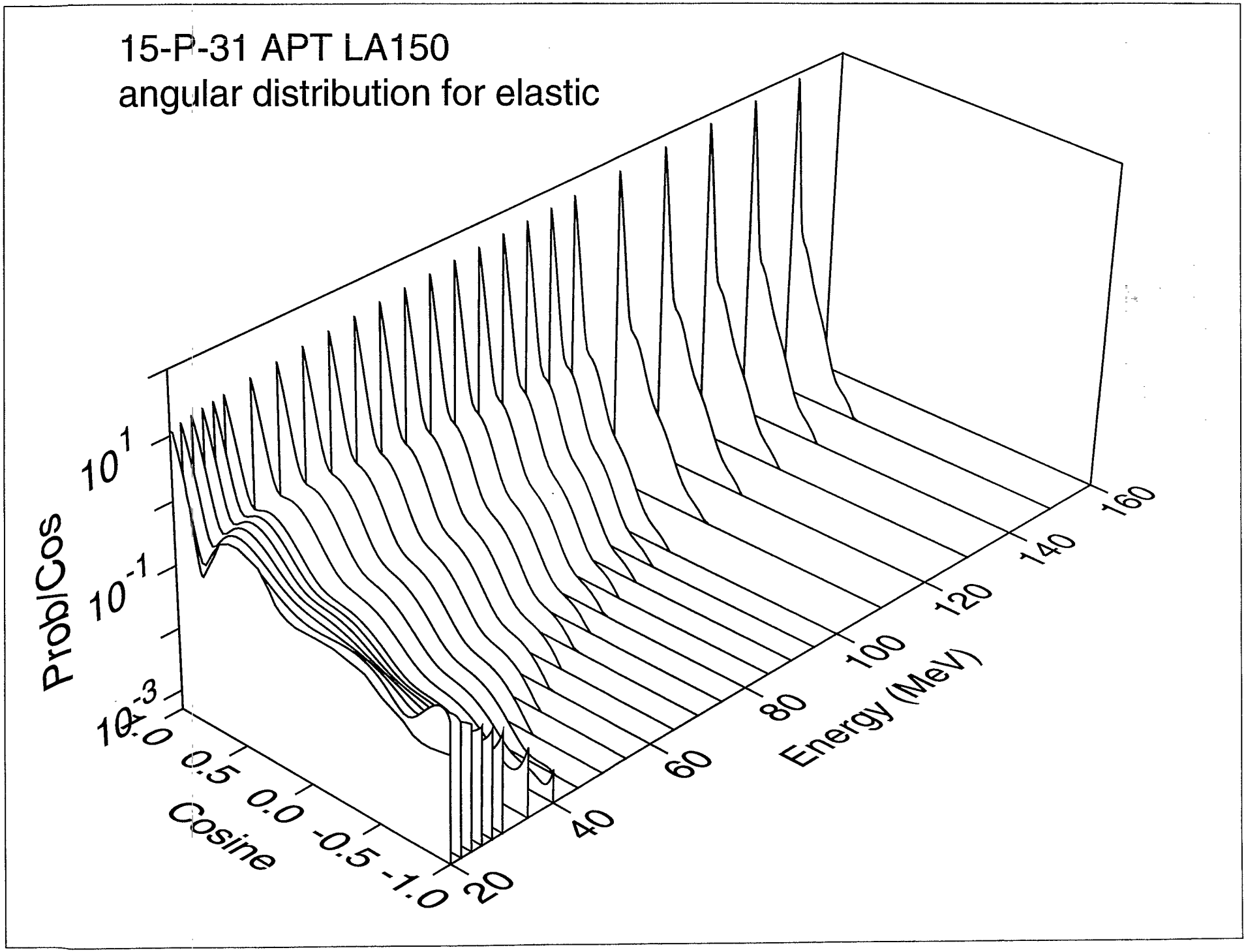
n + ^{31}P Kalbach preequilibrium ratios

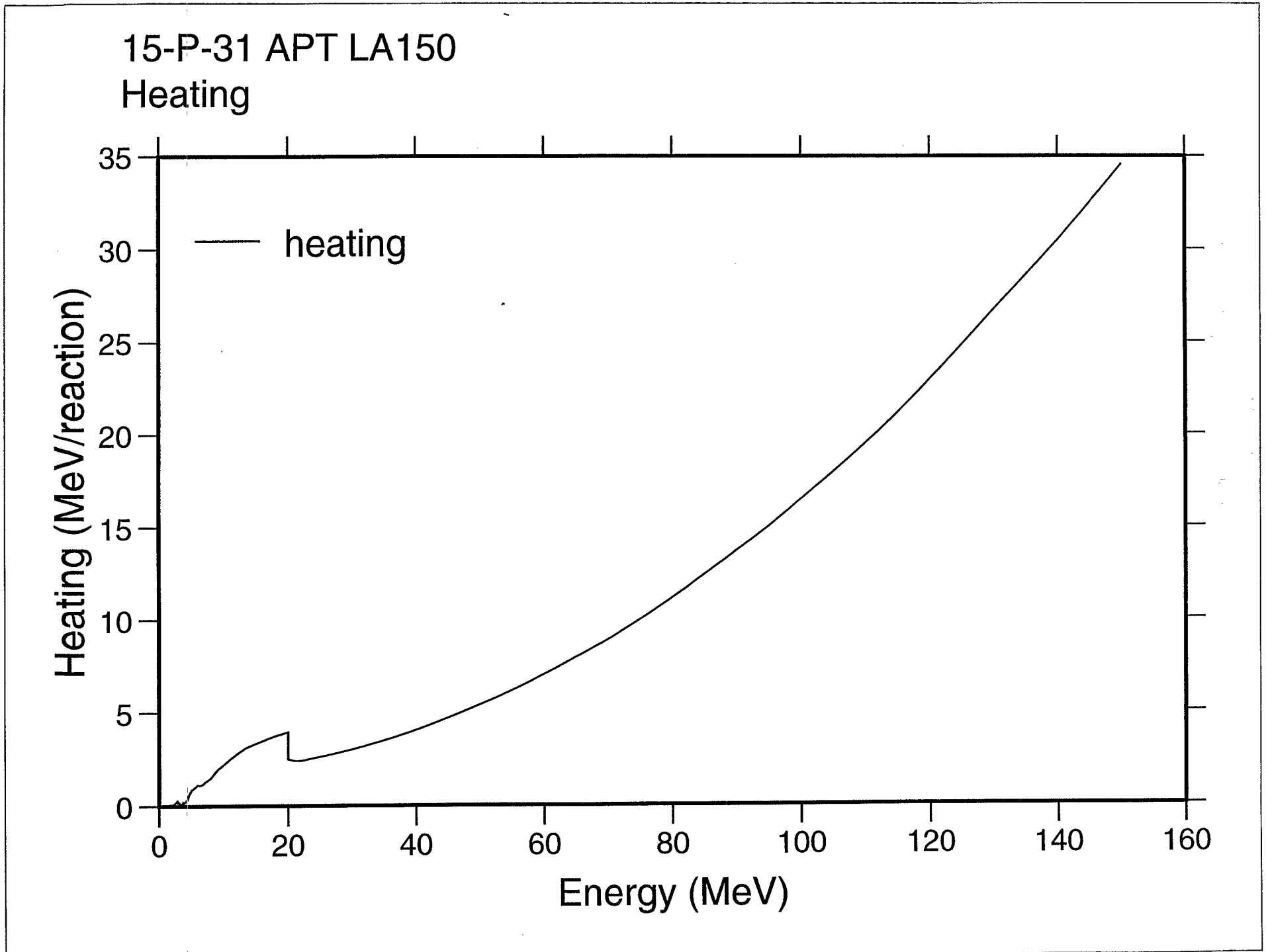


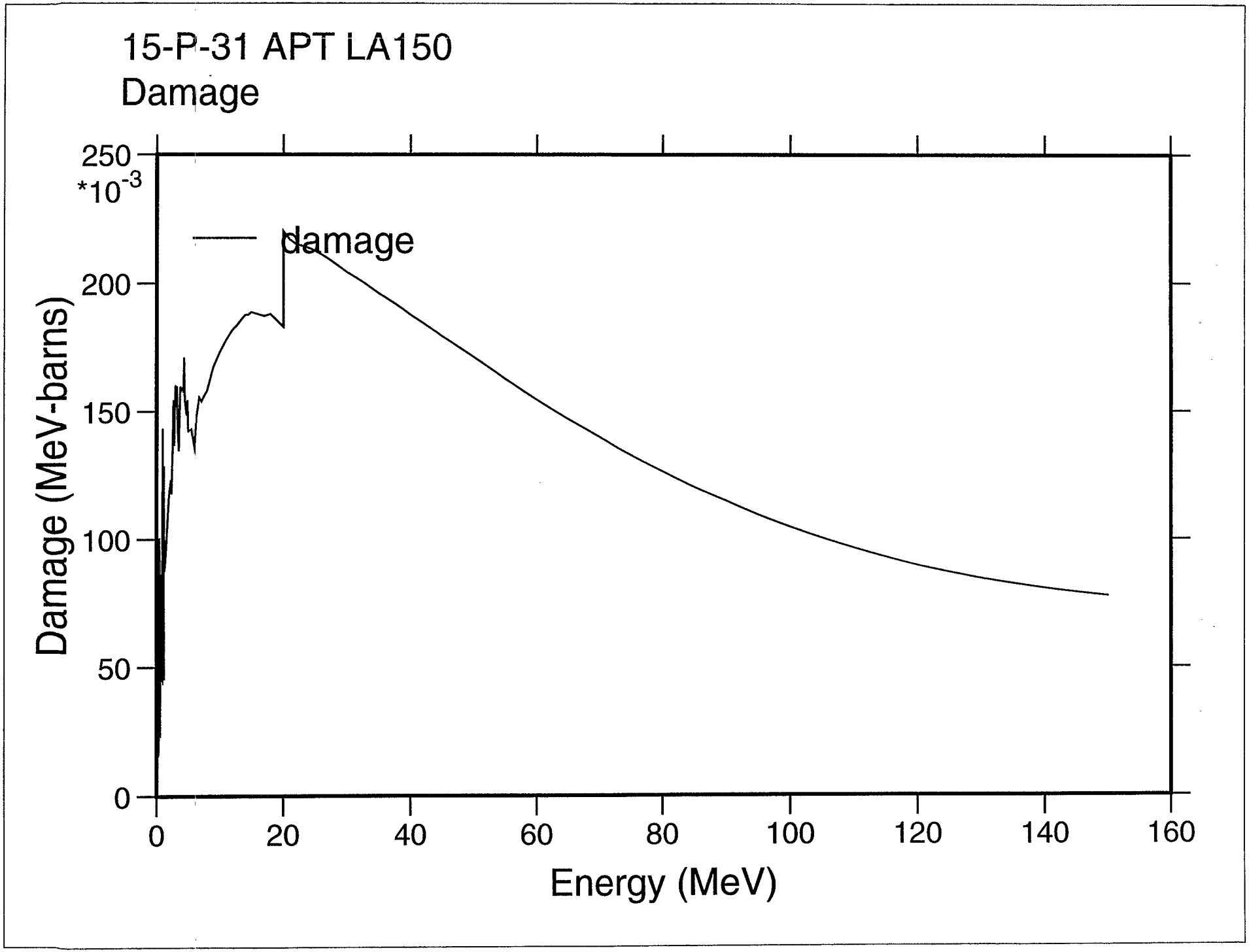







15-P-31 APT LA150
angular distribution for elastic
Prob/Cos
10^{1}
10^{-1}
10^{-3}
1.0
0.5
0.0
-0.5
-1.0
Cosine
20
40
60
80
100
120
140
160
Energy (MeV)


15-P-31 APT LA150
Heating
heating
Heating (MeV/reaction)
Energy (MeV)
0
5
10
15
20
25
30
35
0
20
40
60
80
100
120
140
160


15-P-31 APT LA150
Damage
250
*10-3
damage
200
150
100
50
0
Damage (MeV-barns)
0
20
40
60
80
100
120
140
160
Energy (MeV)