EVALUATION OF p + 60Ni 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 + Ni58 and p + Ni58 reactions (Ch97). 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 (Ch96). 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 Gilbert and Cameron [Gi65] 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).

DETAILS OF THE p + 60Ni ANALYSIS

The neutron optical model potential was adjusted to reproduce the total cross section data((Du67, Bo71, St71, Sm79, Fe80, Pe82, Ha82, Di97), s-wave strength function (Mu81) and elastic scattering angular distritution data (Bo71, Gu85, Tu73, Ya79). The data for natural Ni (Di97) was also used because there was not enough data for Ni-60 above 20 MeV. The data for natural Ni were transformed to the Ni-60 cross section according to A*(2/3) law.

The parameter estimation was carried out based on Marquart-Bayesian approach (Sm91), where ECIS95 code was used for the optical model calculation. We have employed the energy dependence of the optical potential similar to Delaroche's work(De89). The initial potential parameters were adopted from Koning and Delaroche (Ko97). Total of 7 parameters concerning the central potential depth were estimated with associated covariance matrix, while the geometircal parameters were fixed to the result of a similar search for n + Ni-58. Presently obtained potential was used for the calculation of neutron transmission coefficients and DWBA cross sections in the energy region above 20 MeV. Below 20 MeV, the Harper neutron potential (Ha82) was used for the calculation of transmission coefficients.

The proton optical potential was also searched for to obtain a good description of proton-total reaction cross section as predicted by Wellisch-Axen systematic (We96) above 50 MeV. The parameter estimation was carried out by the Marquart-Bayesian approach similar to the neutron OMP, but trying to seek the best parameter to reproduce the reaction cross sections compiled by Carlson (Ca96) and Wellisch values. The experimental data in Carlson (Ca96) was scaled for Ni-60 according to A**(2/3) law. In this search, the geometrical parameters were fixed to be same as the neutron potential. The present potential gives a good description of the proton total reaction cross section from 10 MeV to 250 MeV. However, after some trial and error to reproduce both the elastic scattering and reaction cross section data for Ni-58, we have employed the following combination of proton potentials:

0 to 5 MeV	:	Harper potential (Ha82)
6 to 47 MeV	:	Koning and Delaroche (Ko97)
48 to 260 MeV	:	Present OMP

For deuterons, the Lohr-Haeberli [Lo74] global potential was used; for alpha particles the McFadden-Satchler [Mc66] potential was used; and for tritons the Beccheti-Greenlees [Be71] potential was used. The He-3 channel was ignored.

The direct collective inelastic scattering to the following level in Ni-60 was considered by the DWBA-mode calculation of ECIS95:

Jpi	Ex(MeV)	Deformation length
2+	1.331	0.8535

The deformation length was determined to match the ENDF/B-VI value at 20 MeV for the incident neutron channel.

Certain nuclear level densities were modified from their default values due to experimental information available, as documented in the ENDF-file1 of our n+60Ni evaluation.

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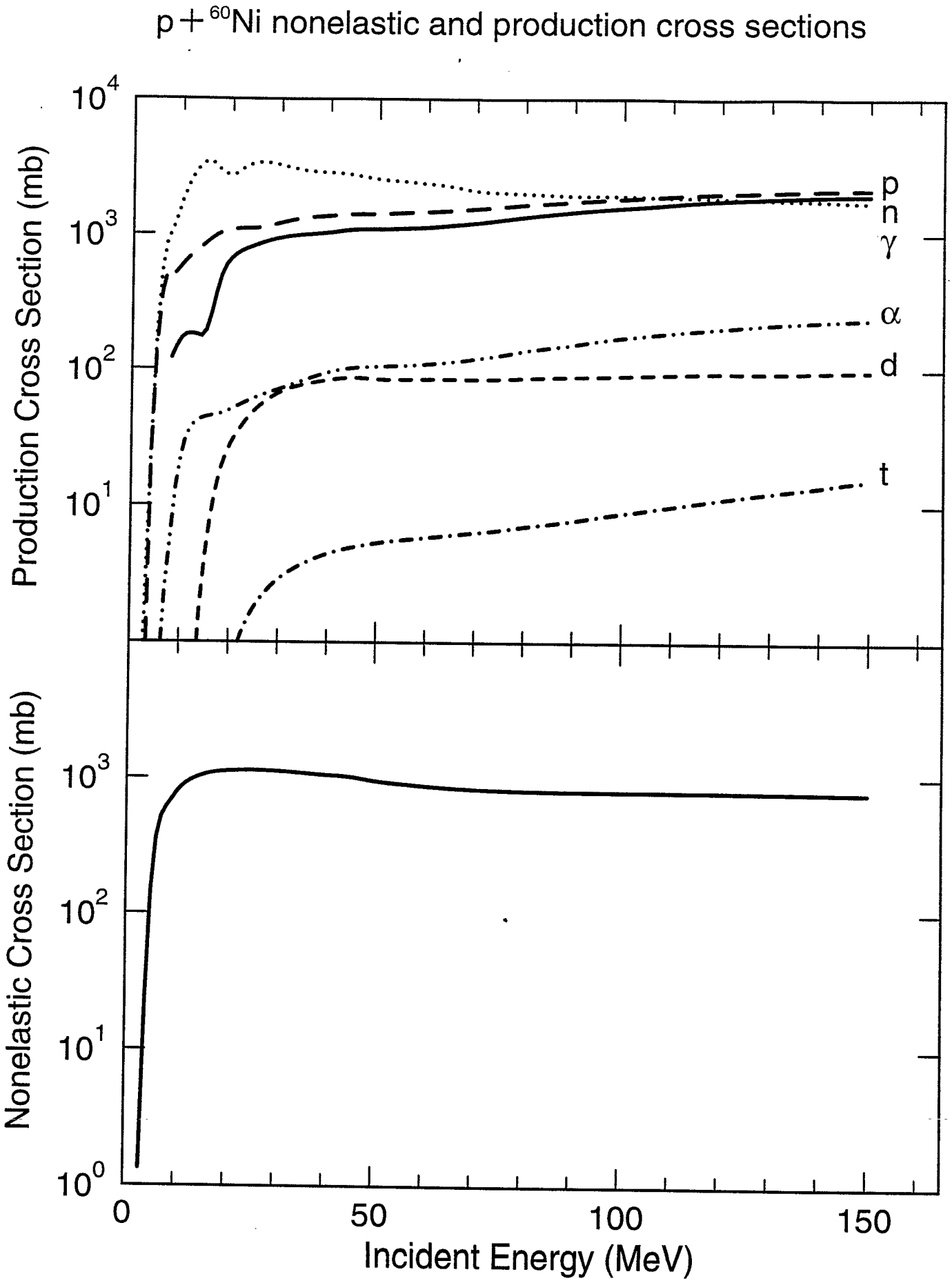
28060 = TARGET 1000Z+A (if A=0 then elemental)
1001 = PROJECTILE 1000Z+A
Nonelastic, elastic, and Production cross sections for A<5 ejectiles in barns:

Energy	nonelas	elastic	neutron	proton	deuteron	triton	helium3	alpha	gamma
2.000E+00	2.707E-04	0.000E+00	0.000E+00	4.956E-09	0.000E+00	0.000E+00	0.000E+00	0.000E+00	4.234E-04
3.000E+00	1.342E-03	0.000E+00	0.000E+00	5.345E-04	0.000E+00	0.000E+00	0.000E+00	2.509E-10	1.728E-03
4.000E+00	2.374E-02	0.000E+00	0.000E+00	2.274E-02	0.000E+00	0.000E+00	0.000E+00	3.210E-07	2.498E-02
5.000E+00	1.450E-01	0.000E+00	0.000E+00	1.440E-01	0.000E+00	0.000E+00	0.000E+00	1.707E-05	1.758E-01
6.000E+00	3.613E-01	0.000E+00	0.000E+00	3.598E-01	0.000E+00	0.000E+00	0.000E+00	4.832E-04	5.436E-01
7.000E+00	5.181E-01	0.000E+00	0.000E+00	5.148E-01	0.000E+00	0.000E+00	0.000E+00	2.466E-03	8.960E-01
8.000E+00	6.064E-01	0.000E+00	1.218E-01	4.782E-01	0.000E+00	0.000E+00	0.000E+00	5.829E-03	1.053E+00
9.000E+00	6.827E-01	0.000E+00	1.461E-01	5.228E-01	0.000E+00	0.000E+00	0.000E+00	1.336E-02	1.346E+00
1.000E+01	7.703E-01	0.000E+00	1.684E-01	5.791E-01	0.000E+00	0.000E+00	0.000E+00	2.244E-02	1.755E+00
1.100E+01	8.491E-01	0.000E+00	1.799E-01	6.374E-01	1.911E-07	0.000E+00	0.000E+00	3.140E-02	2.191E+00
1.200E+01	9.117E-01	0.000E+00	1.819E-01	6.920E-01	3.256E-05	0.000E+00	0.000E+00	3.737E-02	2.603E+00
1.300E+01	9.597E-01	0.000E+00	1.794E-01	7.390E-01	4.065E-04	4.445E-14	0.000E+00	4.075E-02	2.978E+00
1.400E+01	9.991E-01	0.000E+00	1.747E-01	7.936E-01	1.670E-03	6.401E-08	0.000E+00	4.274E-02	3.286E+00
1.500E+01	1.032E+00	0.000E+00	1.934E-01	8.526E-01	4.106E-03	3.730E-06	0.000E+00	4.405E-02	3.467E+00
1.600E+01	1.060E+00	0.000E+00	2.544E-01	9.122E-01	7.809E-03	2.415E-05	0.000E+00	4.484E-02	3.414E+00
1.700E+01	1.081E+00	0.000E+00	3.612E-01	9.679E-01	1.259E-02	6.548E-05	0.000E+00	4.556E-02	3.151E+00
1.800E+01	1.096E+00	0.000E+00	4.832E-01	1.010E+00	1.795E-02	1.487E-04	0.000E+00	4.643E-02	2.855E+00
1.900E+01	1.107E+00	0.000E+00	5.808E-01	1.039E+00	2.289E-02	2.960E-04	0.000E+00	4.782E-02	2.743E+00
2.000E+01	1.115E+00	0.000E+00	6.463E-01	1.059E+00	2.762E-02	5.063E-04	0.000E+00	4.981E-02	2.685E+00
2.200E+01	1.126E+00	0.000E+00	7.357E-01	1.078E+00	3.641E-02	1.018E-03	0.000E+00	5.410E-02	2.970E+00
2.400E+01	1.132E+00	0.000E+00	7.890E-01	1.082E+00	4.526E-02	1.520E-03	0.000E+00	5.847E-02	3.257E+00
2.600E+01	1.133E+00	0.000E+00	8.382E-01	1.097E+00	5.315E-02	1.998E-03	0.000E+00	6.271E-02	3.377E+00
2.800E+01	1.129E+00	0.000E+00	8.850E-01	1.135E+00	6.022E-02	2.447E-03	0.000E+00	6.689E-02	3.319E+00
3.000E+01	1.120E+00	0.000E+00	9.208E-01	1.185E+00	6.645E-02	2.871E-03	0.000E+00	7.063E-02	3.199E+00
3.500E+01	1.087E+00	0.000E+00	9.782E-01	1.293E+00	7.636E-02	3.724E-03	0.000E+00	8.236E-02	2.899E+00
4.000E+01	1.051E+00	0.000E+00	1.017E+00	1.341E+00	8.263E-02	4.422E-03	0.000E+00	9.456E-02	2.801E+00
4.500E+01	1.018E+00	0.000E+00	1.072E+00	1.384E+00	8.611E-02	4.931E-03	0.000E+00	1.019E-01	2.689E+00
5.000E+01	9.494E-01	0.000E+00	1.079E+00	1.389E+00	8.398E-02	5.302E-03	0.000E+00	1.045E-01	2.511E+00
5.500E+01	9.063E-01	0.000E+00	1.091E+00	1.415E+00	8.382E-02	5.587E-03	0.000E+00	1.064E-01	2.415E+00
6.000E+01	8.737E-01	0.000E+00	1.112E+00	1.439E+00	8.431E-02	5.828E-03	0.000E+00	1.092E-01	2.321E+00
6.500E+01	8.481E-01	0.000E+00	1.154E+00	1.475E+00	8.452E-02	6.091E-03	0.000E+00	1.138E-01	2.219E+00
7.000E+01	8.297E-01	0.000E+00	1.200E+00	1.522E+00	8.416E-02	6.362E-03	0.000E+00	1.203E-01	2.056E+00
7.500E+01	8.173E-01	0.000E+00	1.264E+00	1.574E+00	8.499E-02	6.651E-03	0.000E+00	1.282E-01	2.004E+00
8.000E+01	8.094E-01	0.000E+00	1.333E+00	1.634E+00	8.622E-02	7.062E-03	0.000E+00	1.378E-01	1.971E+00
8.500E+01	8.046E-01	0.000E+00	1.395E+00	1.681E+00	8.748E-02	7.426E-03	0.000E+00	1.460E-01	1.939E+00
9.000E+01	8.020E-01	0.000E+00	1.458E+00	1.734E+00	8.868E-02	7.832E-03	0.000E+00	1.544E-01	1.917E+00
9.500E+01	8.005E-01	0.000E+00	1.520E+00	1.790E+00	8.957E-02	8.387E-03	0.000E+00	1.649E-01	1.930E+00
1.000E+02	7.996E-01	0.000E+00	1.574E+00	1.840E+00	9.077E-02	8.871E-03	0.000E+00	1.734E-01	1.928E+00
1.100E+02	7.978E-01	0.000E+00	1.680E+00	1.925E+00	9.301E-02	9.963E-03	0.000E+00	1.892E-01	1.884E+00
1.200E+02	7.951E-01	0.000E+00	1.785E+00	2.003E+00	9.494E-02	1.132E-02	0.000E+00	2.054E-01	1.856E+00
1.300E+02	7.910E-01	0.000E+00	1.864E+00	2.065E+00	9.528E-02	1.263E-02	0.000E+00	2.188E-01	1.817E+00
1.400E+02	7.856E-01	0.000E+00	1.912E+00	2.111E+00	9.676E-02	1.399E-02	0.000E+00	2.298E-01	1.777E+00
1.500E+02	7.792E-01	0.000E+00	1.938E+00	2.137E+00	9.791E-02	1.539E-02	0.000E+00	2.386E-01	1.724E+00

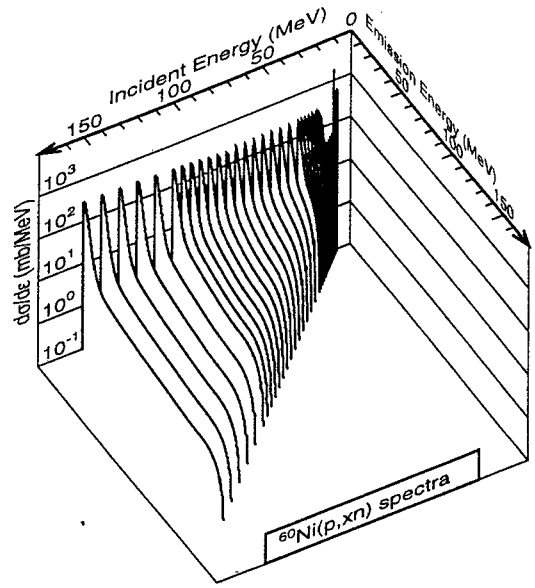
28060 = TARGET 1000Z+A (if A=0 then elemental)
1001 = PROJECTILE 1000Z+A
Aver. lab emission energies for A<5 ejectiles in MeV:

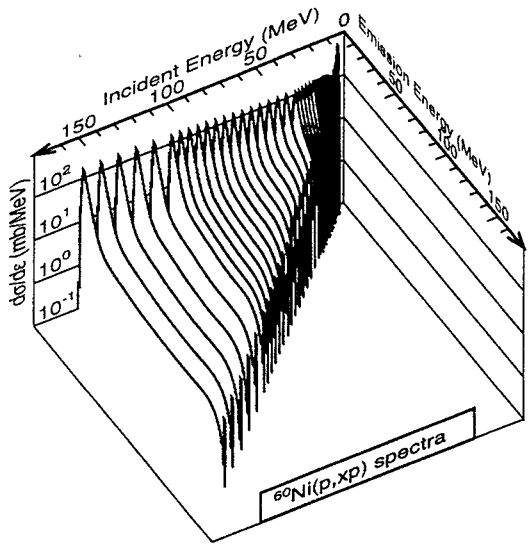
Energy	neutron	proton	deuteron	triton	helium3	alpha	gamma
2.000E+00	0.000E+00	5.473E-04	0.000E+00	0.000E+00	0.000E+00	0.000E+00	3.309E+00
3.000E+00	0.000E+00	1.476E+00	0.000E+00	0.000E+00	0.000E+00	2.485E+00	2.972E+00
4.000E+00	0.000E+00	2.428E+00	0.000E+00	0.000E+00	0.000E+00	3.412E+00	1.409E+00
5.000E+00	0.000E+00	3.261E+00	0.000E+00	0.000E+00	0.000E+00	4.338E+00	1.230E+00
6.000E+00	0.000E+00	3.898E+00	0.000E+00	0.000E+00	0.000E+00	5.255E+00	1.214E+00
7.000E+00	0.000E+00	4.467E+00	0.000E+00	0.000E+00	0.000E+00	5.994E+00	1.295E+00
8.000E+00	6.296E-01	4.949E+00	0.000E+00	0.000E+00	0.000E+00	6.757E+00	1.284E+00
9.000E+00	1.375E+00	5.247E+00	0.000E+00	0.000E+00	0.000E+00	7.418E+00	1.401E+00
1.000E+01	1.734E+00	5.445E+00	0.000E+00	0.000E+00	0.000E+00	7.936E+00	1.521E+00
1.100E+01	2.061E+00	5.632E+00	1.566E+00	0.000E+00	0.000E+00	8.385E+00	1.637E+00
1.200E+01	2.365E+00	5.809E+00	2.418E+00	0.000E+00	0.000E+00	8.765E+00	1.760E+00
1.300E+01	2.637E+00	5.992E+00	3.202E+00	1.067E-02	0.000E+00	9.075E+00	1.884E+00
1.400E+01	2.803E+00	6.125E+00	3.941E+00	1.704E+00	0.000E+00	9.329E+00	1.994E+00
1.500E+01	2.787E+00	6.144E+00	4.555E+00	2.617E+00	0.000E+00	9.526E+00	2.066E+00
1.600E+01	2.428E+00	6.232E+00	5.133E+00	3.472E+00	0.000E+00	9.694E+00	2.065E+00
1.700E+01	2.087E+00	6.331E+00	5.719E+00	3.991E+00	0.000E+00	9.844E+00	1.999E+00
1.800E+01	1.974E+00	6.452E+00	6.316E+00	4.381E+00	0.000E+00	1.000E+01	1.871E+00
1.900E+01	2.032E+00	6.635E+00	6.896E+00	4.746E+00	0.000E+00	1.014E+01	1.742E+00
2.000E+01	2.235E+00	6.851E+00	7.466E+00	5.250E+00	0.000E+00	1.027E+01	1.737E+00
2.200E+01	2.519E+00	7.333E+00	8.543E+00	6.208E+00	0.000E+00	1.057E+01	1.701E+00
2.400E+01	2.900E+00	7.867E+00	9.711E+00	7.151E+00	0.000E+00	1.087E+01	1.761E+00
2.600E+01	3.246E+00	8.339E+00	1.084E+01	8.153E+00	0.000E+00	1.116E+01	1.801E+00
2.800E+01	3.555E+00	8.717E+00	1.199E+01	9.122E+00	0.000E+00	1.140E+01	1.805E+00

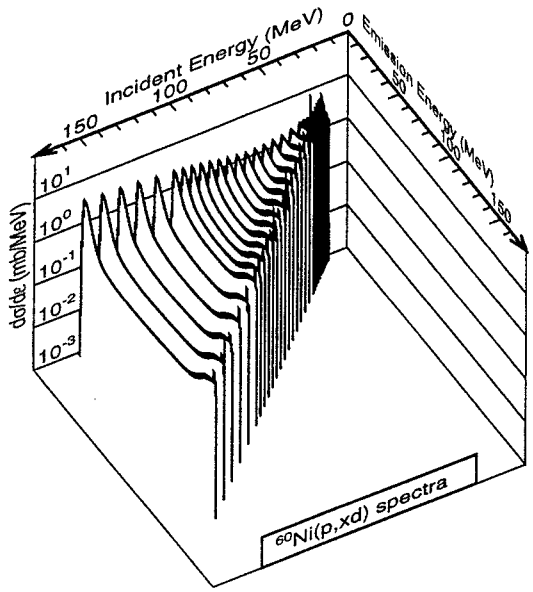
3.000E+01	3.860E+00	9.057E+00	1.315E+01	1.004E+01	0.000E+00	1.161E+01	1.780E+00
3.500E+01	4.648E+00	1.002E+01	1.609E+01	1.207E+01	0.000E+00	1.189E+01	1.689E+00
4.000E+01	5.397E+00	1.117E+01	1.922E+01	1.402E+01	0.000E+00	1.215E+01	1.687E+00
4.500E+01	6.032E+00	1.223E+01	2.231E+01	1.583E+01	0.000E+00	1.246E+01	1.709E+00
5.000E+01	6.632E+00	1.313E+01	2.500E+01	1.746E+01	0.000E+00	1.275E+01	1.699E+00
5.500E+01	7.232E+00	1.394E+01	2.773E+01	1.891E+01	0.000E+00	1.302E+01	1.686E+00
6.000E+01	7.813E+00	1.472E+01	3.047E+01	2.016E+01	0.000E+00	1.323E+01	1.680E+00
6.500E+01	8.289E+00	1.536E+01	3.285E+01	2.098E+01	0.000E+00	1.338E+01	1.686E+00
7.000E+01	8.737E+00	1.587E+01	3.489E+01	2.160E+01	0.000E+00	1.348E+01	1.689E+00
7.500E+01	9.106E+00	1.635E+01	3.706E+01	2.196E+01	0.000E+00	1.354E+01	1.701E+00
8.000E+01	9.452E+00	1.678E+01	3.892E+01	2.190E+01	0.000E+00	1.357E+01	1.721E+00
8.500E+01	9.857E+00	1.735E+01	4.090E+01	2.190E+01	0.000E+00	1.364E+01	1.734E+00
9.000E+01	1.026E+01	1.788E+01	4.275E+01	2.176E+01	0.000E+00	1.371E+01	1.752E+00
9.500E+01	1.065E+01	1.840E+01	4.402E+01	2.130E+01	0.000E+00	1.374E+01	1.744E+00
1.000E+02	1.109E+01	1.896E+01	4.571E+01	2.097E+01	0.000E+00	1.381E+01	1.724E+00
1.100E+02	1.190E+01	2.016E+01	4.889E+01	2.006E+01	0.000E+00	1.395E+01	1.727E+00
1.200E+02	1.261E+01	2.133E+01	5.140E+01	1.893E+01	0.000E+00	1.408E+01	1.732E+00
1.300E+02	1.340E+01	2.264E+01	5.346E+01	1.788E+01	0.000E+00	1.422E+01	1.743E+00
1.400E+02	1.428E+01	2.396E+01	5.632E+01	1.669E+01	0.000E+00	1.437E+01	1.757E+00
1.500E+02	1.522E+01	2.539E+01	5.912E+01	1.548E+01	0.000E+00	1.454E+01	1.773E+00

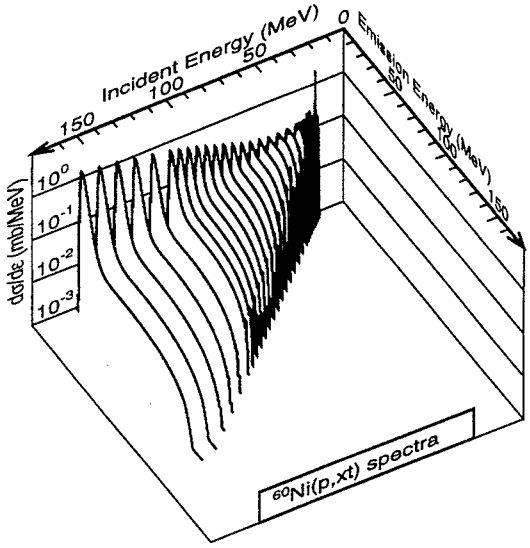

p + 60Ni nonelastic and production cross sections
Production Cross Section (mb)
10^4
10^3
10^2
10^1
p
n
γ
α
d
t
Nonelastic Cross Section (mb)
10^3
10^2
10^1
10^0
0
50
100
150
Incident Energy (MeV)

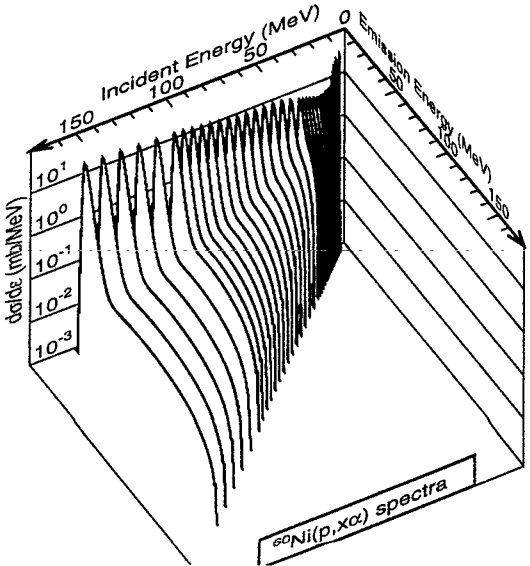
p + ^{60}Ni angle-integrated emission spectra

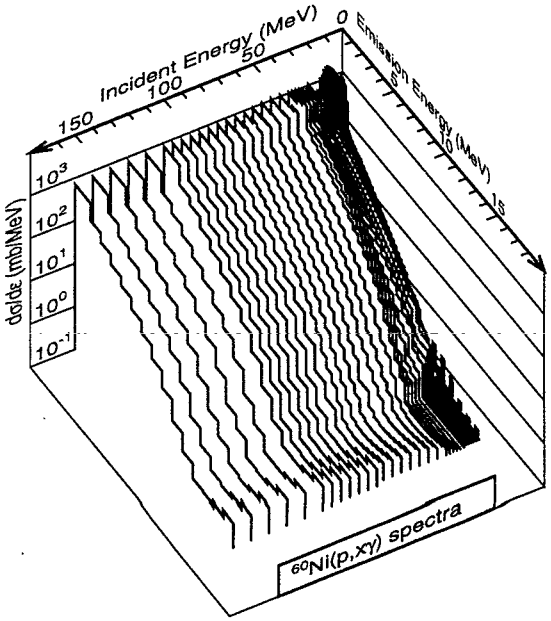




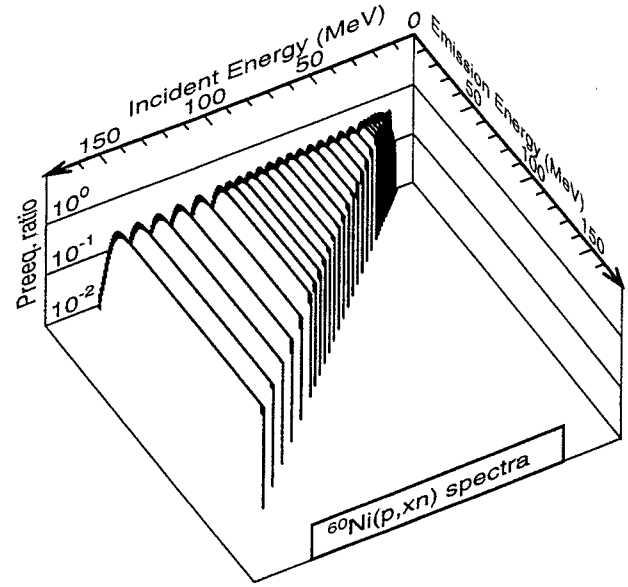


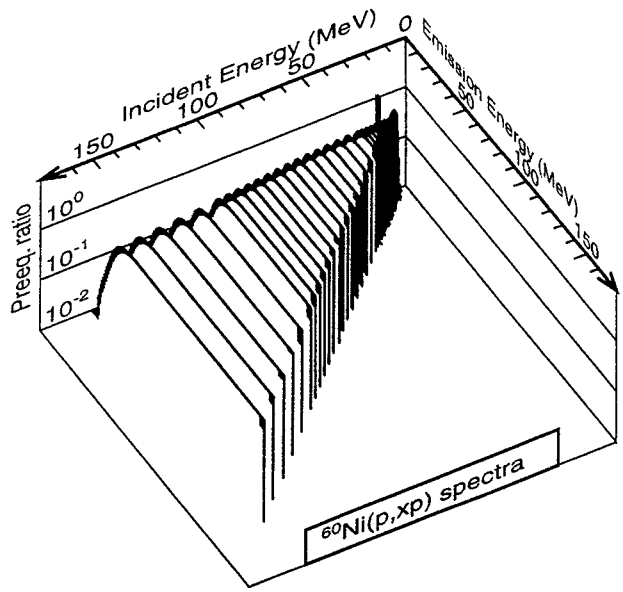


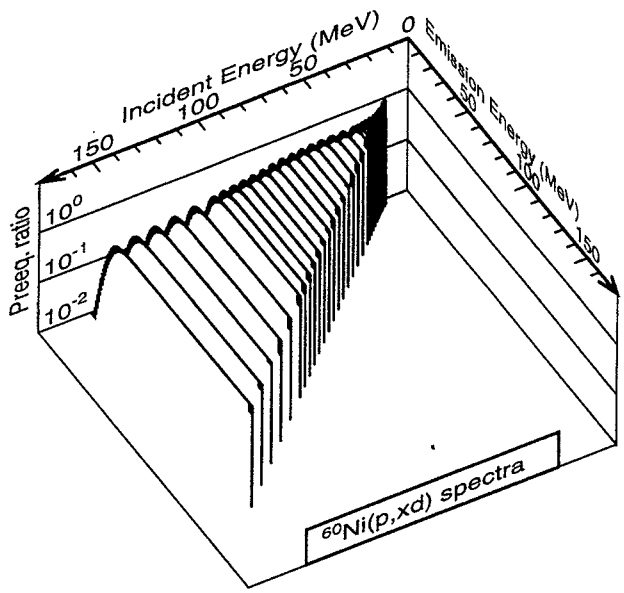


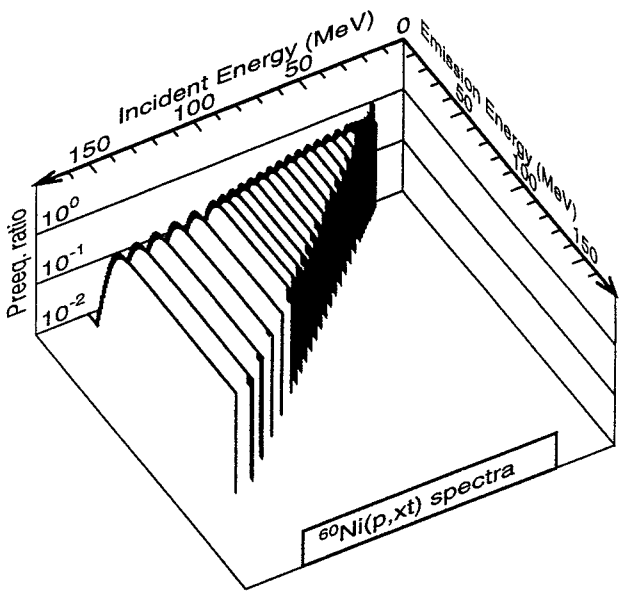


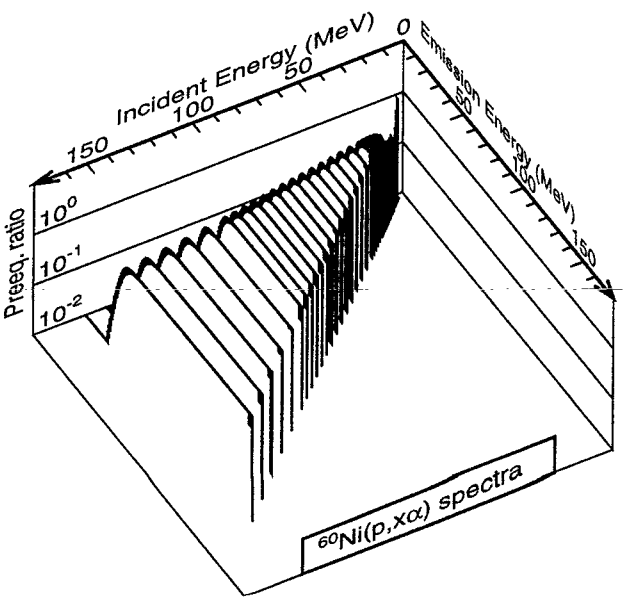
p + ^{60}Ni Kalbach preequilibrium ratios

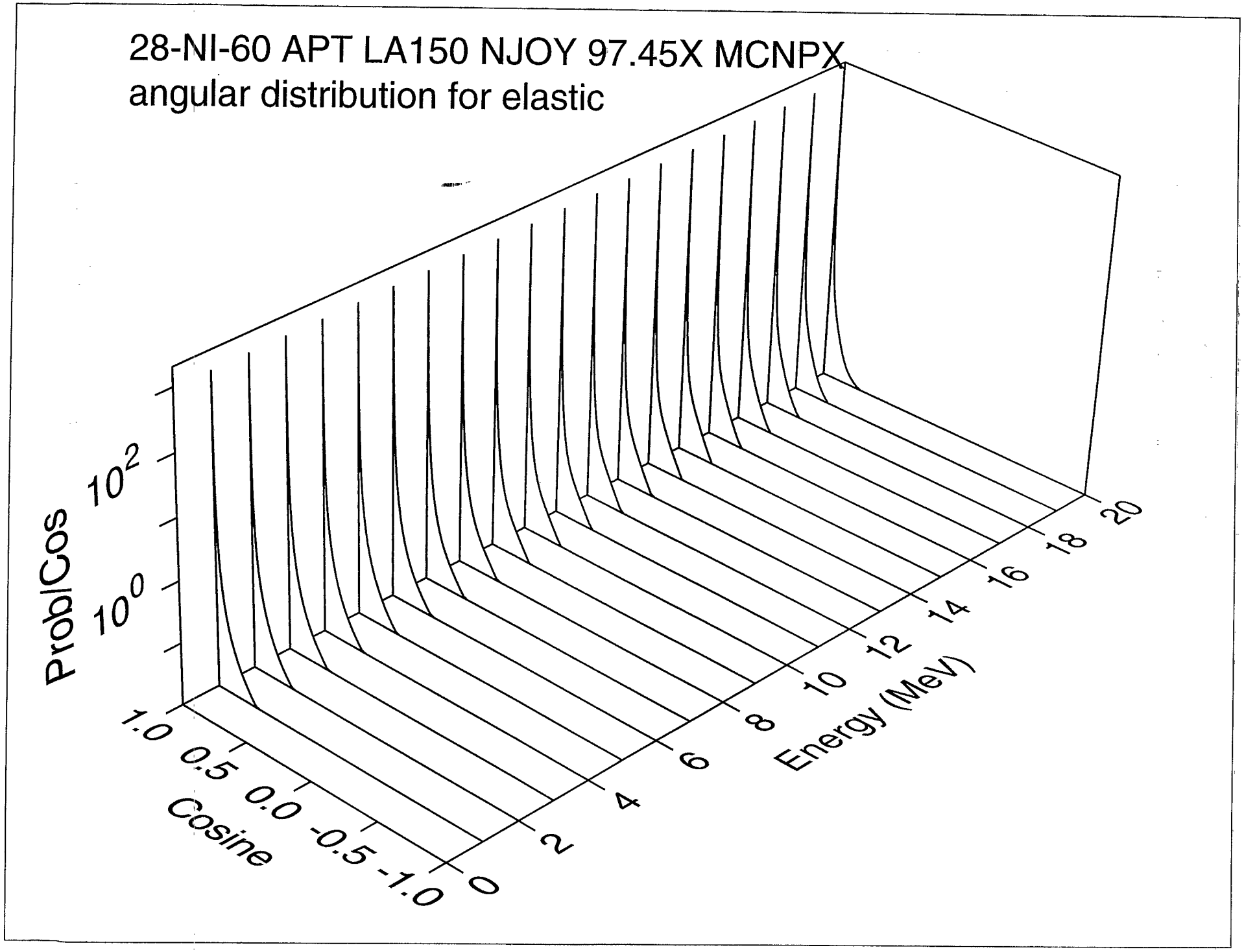


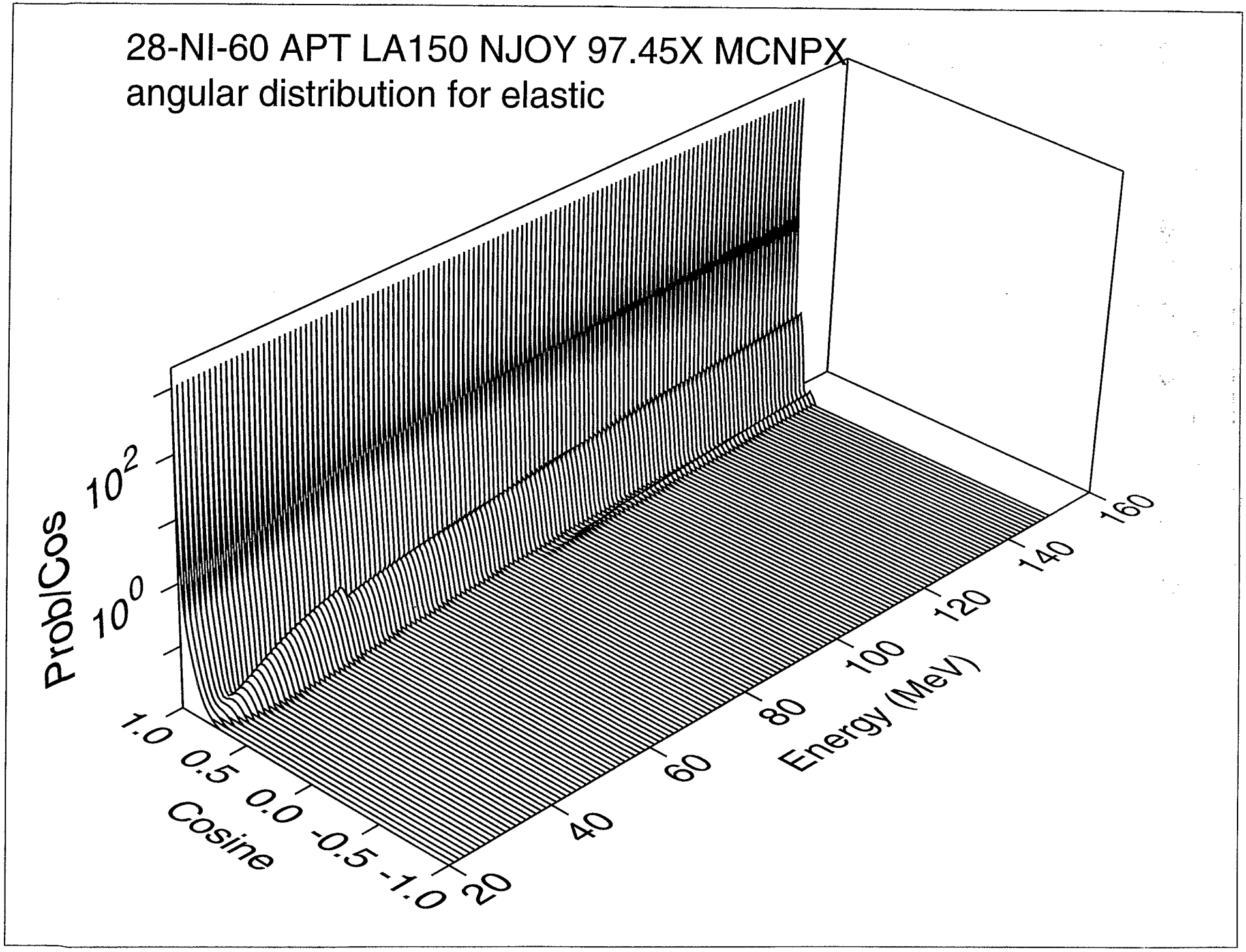


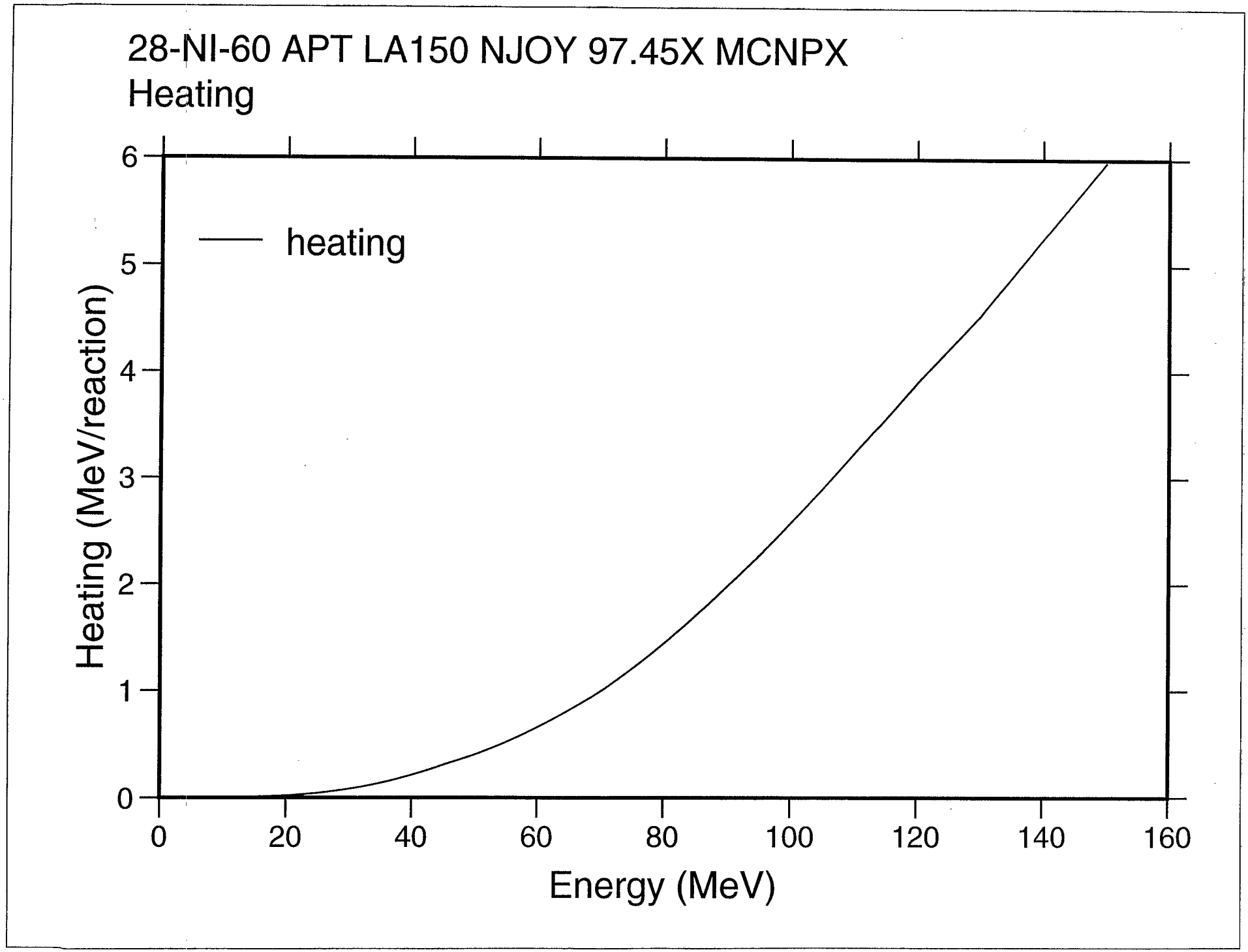







28-NI-60 APT LA150 NJOY 97.45X MCNPX
angular distribution for elastic
Prob/Cos
10^2
10^0
Cosine
1.0
0.5
0.0
-0.5
-1.0
Energy (MeV)
0
2
4
6
8
10
12
14
16
18
20


28-NI-60 APT LA150 NJOY 97.45X MCNPX
angular distribution for elastic
ProbCos
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)


28-NI-60 APT LA150 NJOY 97.45X MCNPX
Heating
heating
Heating (MeV/reaction)
Energy (MeV)
0
1
2
3
4
5
6
0
20
40
60
80
100
120
140
160