EVALUATION OF p + 64Ni CROSS SECTIONS FOR THE ENERGY RANGE 1 to 150 MeV

S. Chiba, M. B. Chadwick, P. G. Young, and A. J. Koning

24 September 1997

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 + 64Ni ANALYSIS

The neutron optical model potential was adjusted to reproduce the measured total cross section data (Ci68, Pe73, Sc73, La83, Di97, Fa66, Du67) and s-wave strength function (Mu81). The data for natural Ni were also used because there was not enough data for Ni-64 at MeV region. The data for natural Ni were transformed to the Ni-64 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 geometrical 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 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-64 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 levels in Ni-64 was considered by the DWBA-mode calculation of ECIS95 (Ra96):

Jpi	Ex(MeV)	Deformation length
2+	1.3458	0.92149
3-	3.56	0.838

The data for 2+ was retrieved from the literature (Ra87). The deformation length for the 3- level scaled from that of Ni-62 according to A**(1/3) law.

****

REFERENCES

[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.

[Ca96]. R. F. Carlson, Atomic Data and Nuclear Data Tables, 63, 93(1996).

[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).

[Ch96]. 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.

[Ch97]. M. B. Chadwick and P. G. Young, "Model Calculations of n,p + 58,60,61,62,64Ni" in APT PROGRESS REPORT: 1 August - 1 September 1997, internal Los Alamos National Laboratory memo T-2-97/MS-51, 8 September 1997 from R.E. MacFarlane to L. Waters.

[Ci68]. S. Cierjack et al, KFK-1000(1968).

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

[De89]. J.P. Delaroche, Y. Wang and J. Rapaport, Phys. Rev. C39, 391(1989).

[Di97]. F. Dietrich et al., private communication (1997).

[Du67]. Ju. V. Dukarevich et al., Nucl. Phys. A92, 433(1967).

[Fa66]. J.A. Farrel et al, AP 36, 367(1966).

[Gi65]. A. Gilbert and A. G. W. Cameron, "A Composite Nuclear-Level Density Formula with Shell Corrections," Can. J. Phys. 43, 1446 (1965).

[Gu85]. P.P. Guss et al, Nucl. Phys. A438, 187(1985).

[Ha82]. R.C. Harper and W.L. Alford, J. Phys. G. 8, 153(1982).

[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).

[Ko97]. A. Koning and J.P. Delaroche, private communication.

[La83]. D.C. Larson et al, ORNL-TM-8203(1983).

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

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

[Mu81]. S.F. Mughabghab, M. Divadeenam and N.E. Holden, "Neutron Cross Sections", Vol. 1, Part A, Academic Press (1981).

[Pe73]. F.G. Perey, EXFOR 10342002 (1973).

[Pe88]. Pedroni et al, Phys. Rev. C38, 2052(1988).

[Ra87]. S. Raman et al, At. Data Nucl. Data Tables, 36, 1(1987).

[Ra96]. J. Raynal, "Notes on ECIS94", Service de Physique Theorique, Saclay, France (personal communication through A. J. Koning, 1996).

[Sc73]. W. Schimmerling et al., Phys. Rev. C7, 248(1973).

[Sm91]. D.L. Smith, "Probability, Statistics, and Data Uncertainty in Nuclear Science and Technology", American Nuclear Society (1991).

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

[Tu73]. A.I. Tutubalin et al., EXFOR40417005 (73Kiev).

[Ya79]. Y. Yamanouti et al, EXFOR 10953002 (79Knox).

[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).

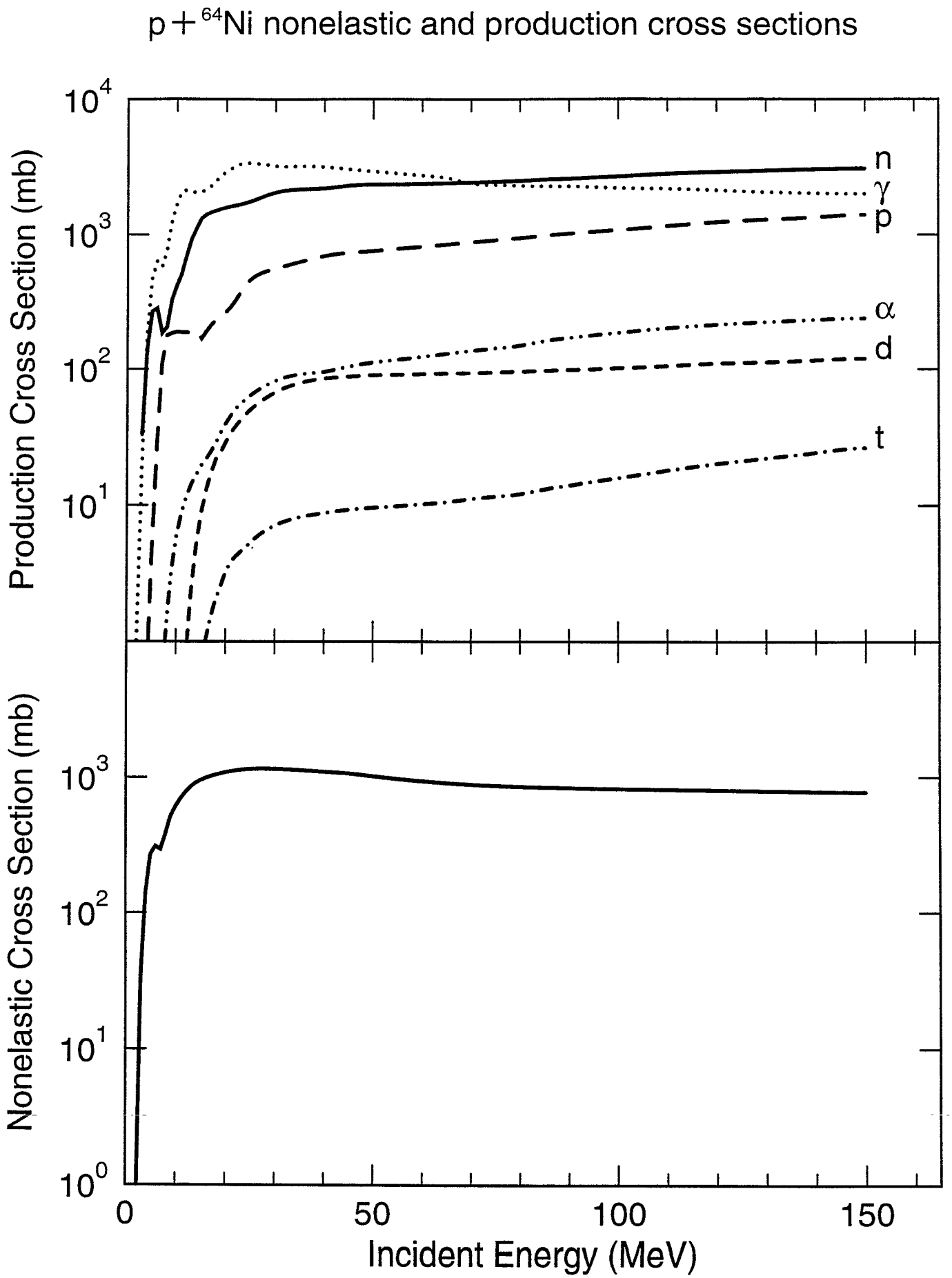
28064 = TARGET 1000Z+A (if A=0 then elemental)
1001 = PROJECTILE 1000Z+A
Nonelastic, elastic, and Production cross sections for A<5 ejectiles in barns:

Energy	nonelas	elastic	neutron	proton	deuteron	triton	helium3	alpha	gamma
2.000E+00	7.871E-04	0.000E+00	0.000E+00	9.915E-09	0.000E+00	0.000E+00	0.000E+00	2.159E-11	1.021E-03
3.000E+00	3.316E-02	0.000E+00	3.307E-02	5.574E-06	0.000E+00	0.000E+00	0.000E+00	3.568E-08	2.022E-02
4.000E+00	1.407E-01	0.000E+00	1.402E-01	3.808E-04	0.000E+00	0.000E+00	0.000E+00	7.047E-07	1.834E-01
5.000E+00	2.719E-01	0.000E+00	2.674E-01	4.356E-03	0.000E+00	0.000E+00	0.000E+00	2.924E-05	4.743E-01
6.000E+00	3.096E-01	0.000E+00	2.820E-01	2.723E-02	0.000E+00	0.000E+00	0.000E+00	1.705E-04	6.377E-01
7.000E+00	2.947E-01	0.000E+00	1.846E-01	1.095E-01	0.000E+00	0.000E+00	0.000E+00	4.582E-04	5.771E-01
8.000E+00	3.822E-01	0.000E+00	2.040E-01	1.767E-01	0.000E+00	0.000E+00	0.000E+00	1.286E-03	7.804E-01
9.000E+00	5.154E-01	0.000E+00	3.280E-01	1.838E-01	4.607E-09	1.870E-08	0.000E+00	3.321E-03	1.284E+00
1.000E+01	6.088E-01	0.000E+00	4.145E-01	1.880E-01	5.214E-06	3.713E-08	0.000E+00	5.907E-03	1.715E+00
1.100E+01	6.941E-01	0.000E+00	5.135E-01	1.868E-01	1.161E-04	3.401E-06	0.000E+00	8.761E-03	2.103E+00
1.200E+01	7.757E-01	0.000E+00	7.069E-01	1.864E-01	7.273E-04	3.212E-05	0.000E+00	1.162E-02	2.141E+00
1.300E+01	8.498E-01	0.000E+00	9.296E-01	1.841E-01	2.338E-03	1.239E-04	0.000E+00	1.433E-02	2.085E+00
1.400E+01	9.089E-01	0.000E+00	1.118E+00	1.896E-01	5.037E-03	3.138E-04	0.000E+00	1.680E-02	2.046E+00
1.500E+01	9.522E-01	0.000E+00	1.318E+00	1.675E-01	8.681E-03	6.454E-04	0.000E+00	1.963E-02	2.080E+00
1.600E+01	9.866E-01	0.000E+00	1.406E+00	1.896E-01	1.285E-02	1.029E-03	0.000E+00	2.196E-02	2.162E+00
1.700E+01	1.016E+00	0.000E+00	1.464E+00	2.122E-01	1.729E-02	1.514E-03	0.000E+00	2.498E-02	2.305E+00
1.800E+01	1.042E+00	0.000E+00	1.507E+00	2.315E-01	2.183E-02	2.024E-03	0.000E+00	2.902E-02	2.513E+00
1.900E+01	1.066E+00	0.000E+00	1.549E+00	2.475E-01	2.476E-02	2.544E-03	0.000E+00	3.446E-02	2.740E+00
2.000E+01	1.087E+00	0.000E+00	1.586E+00	2.633E-01	2.923E-02	3.236E-03	0.000E+00	4.011E-02	2.903E+00
2.200E+01	1.121E+00	0.000E+00	1.644E+00	3.253E-01	3.811E-02	4.190E-03	0.000E+00	5.102E-02	3.214E+00
2.400E+01	1.145E+00	0.000E+00	1.708E+00	4.173E-01	4.622E-02	4.872E-03	0.000E+00	5.999E-02	3.372E+00
2.600E+01	1.156E+00	0.000E+00	1.806E+00	4.872E-01	5.378E-02	5.721E-03	0.000E+00	6.811E-02	3.339E+00
2.800E+01	1.158E+00	0.000E+00	1.928E+00	5.246E-01	6.078E-02	6.468E-03	0.000E+00	7.526E-02	3.278E+00
3.000E+01	1.154E+00	0.000E+00	2.034E+00	5.502E-01	6.709E-02	7.092E-03	0.000E+00	8.150E-02	3.200E+00
3.500E+01	1.132E+00	0.000E+00	2.144E+00	6.200E-01	7.849E-02	8.164E-03	0.000E+00	9.124E-02	3.180E+00
4.000E+01	1.102E+00	0.000E+00	2.183E+00	6.884E-01	8.484E-02	8.789E-03	0.000E+00	9.519E-02	3.137E+00
4.500E+01	1.071E+00	0.000E+00	2.283E+00	7.311E-01	8.758E-02	9.285E-03	0.000E+00	1.040E-01	3.018E+00
5.000E+01	1.020E+00	0.000E+00	2.327E+00	7.517E-01	8.973E-02	9.619E-03	0.000E+00	1.112E-01	2.905E+00
5.500E+01	9.747E-01	0.000E+00	2.335E+00	7.790E-01	9.049E-02	9.867E-03	0.000E+00	1.165E-01	2.808E+00
6.000E+01	9.377E-01	0.000E+00	2.352E+00	8.064E-01	9.158E-02	1.021E-02	0.000E+00	1.228E-01	2.713E+00
6.500E+01	9.079E-01	0.000E+00	2.382E+00	8.353E-01	9.260E-02	1.058E-02	0.000E+00	1.297E-01	2.602E+00
7.000E+01	8.850E-01	0.000E+00	2.412E+00	8.666E-01	9.341E-02	1.116E-02	0.000E+00	1.365E-01	2.362E+00
7.500E+01	8.677E-01	0.000E+00	2.449E+00	8.992E-01	9.470E-02	1.163E-02	0.000E+00	1.428E-01	2.316E+00
8.000E+01	8.547E-01	0.000E+00	2.488E+00	9.329E-01	9.598E-02	1.217E-02	0.000E+00	1.492E-01	2.289E+00
8.500E+01	8.447E-01	0.000E+00	2.552E+00	9.741E-01	9.690E-02	1.319E-02	0.000E+00	1.609E-01	2.271E+00
9.000E+01	8.368E-01	0.000E+00	2.598E+00	1.013E+00	9.849E-02	1.405E-02	0.000E+00	1.700E-01	2.279E+00
9.500E+01	8.302E-01	0.000E+00	2.653E+00	1.049E+00	1.002E-01	1.497E-02	0.000E+00	1.784E-01	2.254E+00
1.000E+02	8.244E-01	0.000E+00	2.704E+00	1.086E+00	1.020E-01	1.590E-02	0.000E+00	1.859E-01	2.224E+00
1.100E+02	8.143E-01	0.000E+00	2.804E+00	1.160E+00	1.055E-01	1.806E-02	0.000E+00	2.009E-01	2.177E+00
1.200E+02	8.049E-01	0.000E+00	2.895E+00	1.229E+00	1.097E-01	2.022E-02	0.000E+00	2.133E-01	2.122E+00
1.300E+02	7.959E-01	0.000E+00	2.971E+00	1.293E+00	1.122E-01	2.223E-02	0.000E+00	2.233E-01	2.065E+00
1.400E+02	7.871E-01	0.000E+00	3.029E+00	1.349E+00	1.163E-01	2.442E-02	0.000E+00	2.322E-01	2.024E+00
1.500E+02	7.785E-01	0.000E+00	3.065E+00	1.398E+00	1.194E-01	2.647E-02	0.000E+00	2.390E-01	2.000E+00

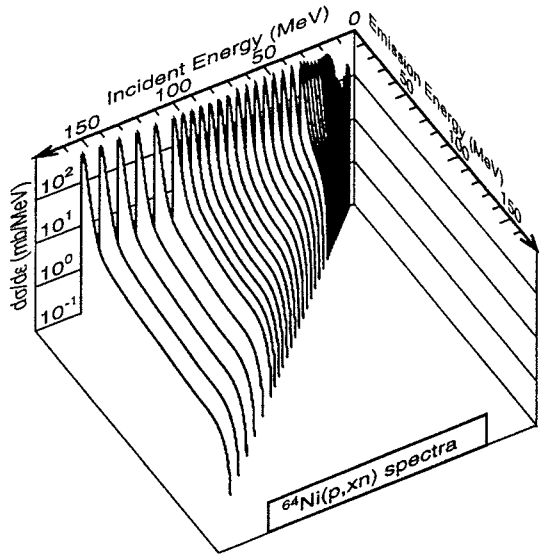
28064 = TARGET 1000Z+A (if A=0 then elemental)
1001 = PROJECTILE 1000Z+A
Aver. lab emission energies for A<5 ejectiles in MeV:

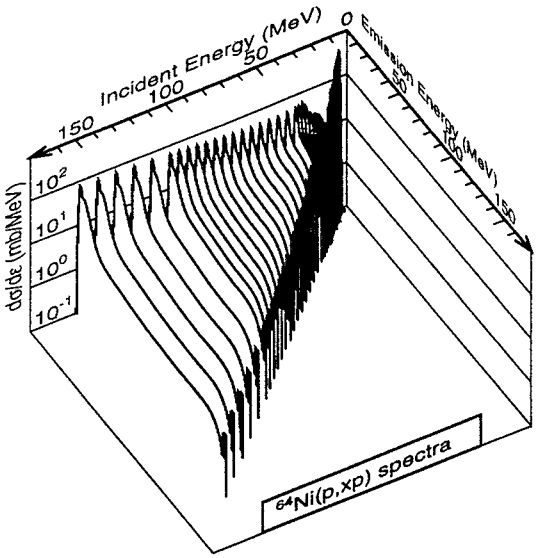
Energy	neutron	proton	deuteron	triton	helium3	alpha	gamma
2.000E+00	0.000E+00	1.923E+00	0.000E+00	0.000E+00	0.000E+00	2.471E+00	4.571E+00
3.000E+00	2.947E-01	1.489E+00	0.000E+00	0.000E+00	0.000E+00	3.303E+00	2.120E-01
4.000E+00	9.391E-01	2.445E+00	0.000E+00	0.000E+00	0.000E+00	4.179E+00	3.661E-01
5.000E+00	1.382E+00	3.371E+00	0.000E+00	0.000E+00	0.000E+00	5.095E+00	5.817E-01
6.000E+00	1.701E+00	4.334E+00	0.000E+00	0.000E+00	0.000E+00	5.816E+00	8.072E-01
7.000E+00	1.968E+00	5.381E+00	0.000E+00	0.000E+00	0.000E+00	6.538E+00	1.022E+00
8.000E+00	2.172E+00	6.335E+00	0.000E+00	0.000E+00	0.000E+00	7.228E+00	1.146E+00
9.000E+00	2.276E+00	7.049E+00	1.282E+00	7.450E-01	0.000E+00	7.766E+00	1.281E+00
1.000E+01	2.411E+00	7.734E+00	2.208E+00	1.682E+00	0.000E+00	8.175E+00	1.410E+00
1.100E+01	2.443E+00	8.483E+00	3.083E+00	2.604E+00	0.000E+00	8.519E+00	1.518E+00
1.200E+01	2.236E+00	9.148E+00	3.791E+00	3.417E+00	0.000E+00	8.850E+00	1.520E+00
1.300E+01	2.131E+00	9.633E+00	4.453E+00	3.900E+00	0.000E+00	9.144E+00	1.481E+00
1.400E+01	2.136E+00	9.959E+00	5.105E+00	4.414E+00	0.000E+00	9.415E+00	1.422E+00
1.500E+01	2.210E+00	9.418E+00	5.768E+00	4.844E+00	0.000E+00	9.643E+00	1.371E+00
1.600E+01	2.346E+00	9.639E+00	6.425E+00	5.332E+00	0.000E+00	9.841E+00	1.344E+00
1.700E+01	2.497E+00	9.830E+00	7.088E+00	5.828E+00	0.000E+00	9.943E+00	1.362E+00
1.800E+01	2.657E+00	1.001E+01	7.736E+00	6.309E+00	0.000E+00	9.949E+00	1.400E+00
1.900E+01	2.799E+00	1.014E+01	8.281E+00	6.800E+00	0.000E+00	9.961E+00	1.446E+00
2.000E+01	2.951E+00	1.024E+01	8.866E+00	7.339E+00	0.000E+00	1.005E+01	1.569E+00
2.200E+01	3.180E+00	9.964E+00	1.007E+01	8.286E+00	0.000E+00	1.023E+01	1.651E+00
2.400E+01	3.347E+00	9.524E+00	1.120E+01	9.028E+00	0.000E+00	1.041E+01	1.656E+00
2.600E+01	3.439E+00	9.707E+00	1.232E+01	9.809E+00	0.000E+00	1.045E+01	1.637E+00
2.800E+01	3.519E+00	1.034E+01	1.342E+01	1.057E+01	0.000E+00	1.051E+01	1.555E+00

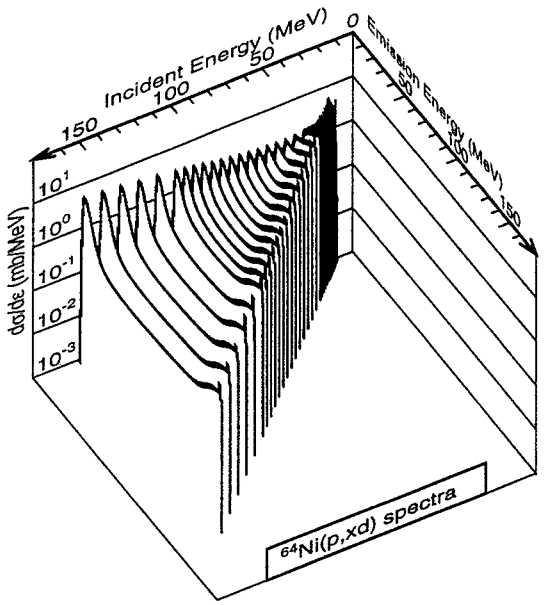
3.000E+01	3.639E+00	1.122E+01	1.456E+01	1.132E+01	0.000E+00	1.063E+01	1.483E+00
3.500E+01	4.089E+00	1.330E+01	1.746E+01	1.316E+01	0.000E+00	1.109E+01	1.459E+00
4.000E+01	4.549E+00	1.508E+01	2.037E+01	1.485E+01	0.000E+00	1.149E+01	1.496E+00
4.500E+01	4.900E+00	1.642E+01	2.304E+01	1.629E+01	0.000E+00	1.165E+01	1.508E+00
5.000E+01	5.247E+00	1.755E+01	2.579E+01	1.757E+01	0.000E+00	1.185E+01	1.521E+00
5.500E+01	5.601E+00	1.884E+01	2.833E+01	1.867E+01	0.000E+00	1.203E+01	1.533E+00
6.000E+01	5.952E+00	1.998E+01	3.074E+01	1.935E+01	0.000E+00	1.215E+01	1.544E+00
6.500E+01	6.279E+00	2.101E+01	3.306E+01	1.988E+01	0.000E+00	1.226E+01	1.545E+00
7.000E+01	6.637E+00	2.195E+01	3.503E+01	2.010E+01	0.000E+00	1.237E+01	1.514E+00
7.500E+01	6.993E+00	2.285E+01	3.713E+01	2.015E+01	0.000E+00	1.247E+01	1.523E+00
8.000E+01	7.351E+00	2.376E+01	3.912E+01	2.010E+01	0.000E+00	1.257E+01	1.533E+00
8.500E+01	7.635E+00	2.429E+01	4.029E+01	1.941E+01	0.000E+00	1.263E+01	1.565E+00
9.000E+01	7.968E+00	2.493E+01	4.178E+01	1.893E+01	0.000E+00	1.271E+01	1.585E+00
9.500E+01	8.272E+00	2.562E+01	4.316E+01	1.843E+01	0.000E+00	1.279E+01	1.585E+00
1.000E+02	8.580E+00	2.631E+01	4.445E+01	1.790E+01	0.000E+00	1.288E+01	1.611E+00
1.100E+02	9.155E+00	2.759E+01	4.626E+01	1.664E+01	0.000E+00	1.305E+01	1.625E+00
1.200E+02	9.693E+00	2.888E+01	4.814E+01	1.535E+01	0.000E+00	1.322E+01	1.598E+00
1.300E+02	1.026E+01	3.020E+01	4.911E+01	1.420E+01	0.000E+00	1.339E+01	1.626E+00
1.400E+02	1.079E+01	3.150E+01	5.059E+01	1.317E+01	0.000E+00	1.354E+01	1.619E+00
1.500E+02	1.138E+01	3.292E+01	5.183E+01	1.238E+01	0.000E+00	1.370E+01	1.647E+00

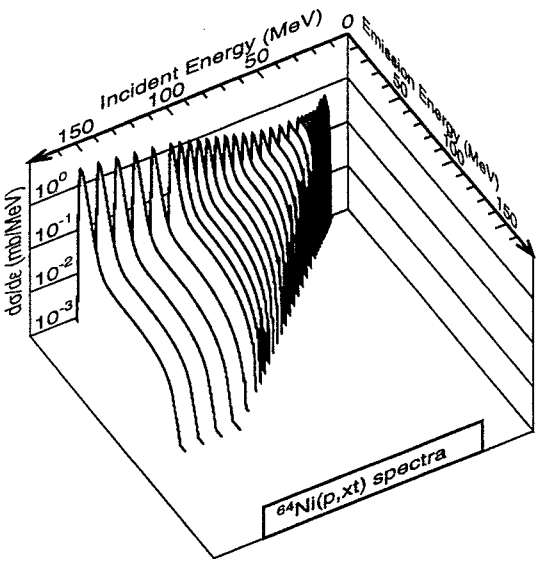

p + 64Ni nonelastic and production cross sections
Production Cross Section (mb)
Nonelastic Cross Section (mb)
Incident Energy (MeV)
n
γ
p
α
d
t
10^4
10^3
10^2
10^1
10^0
0
50
100
150

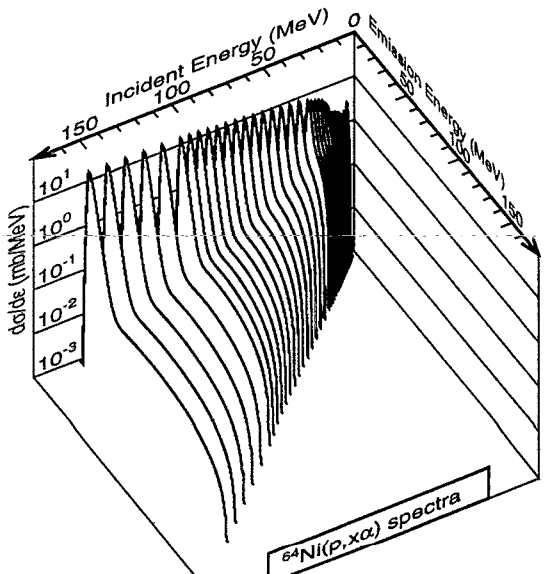
p + ^{64}Ni angle-integrated emission spectra

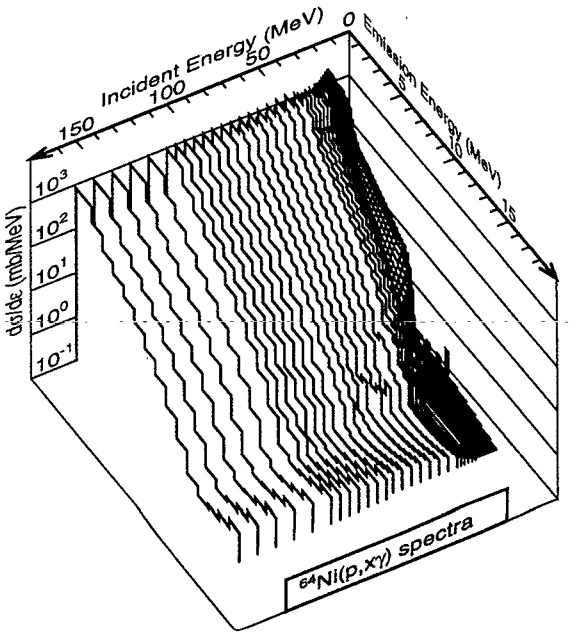




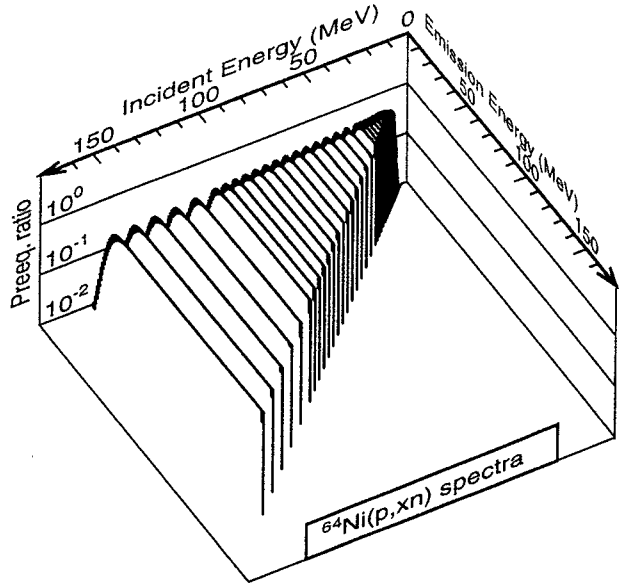


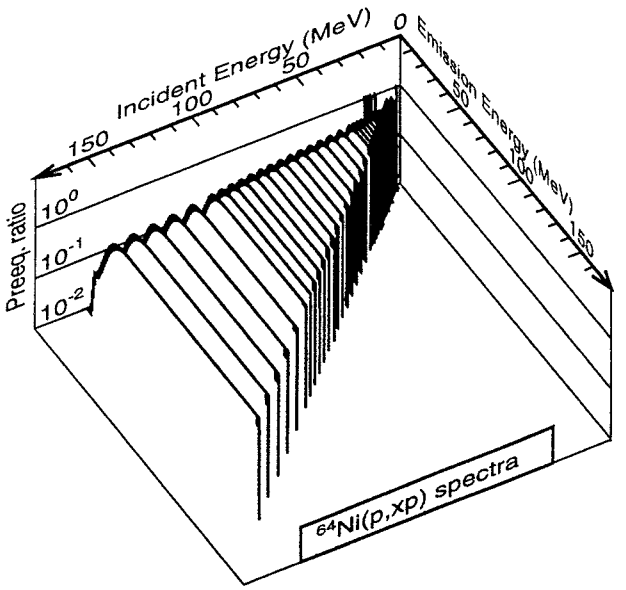


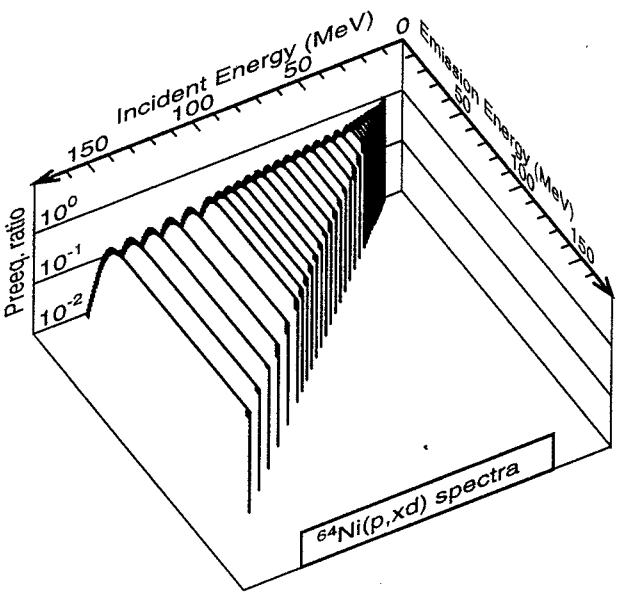


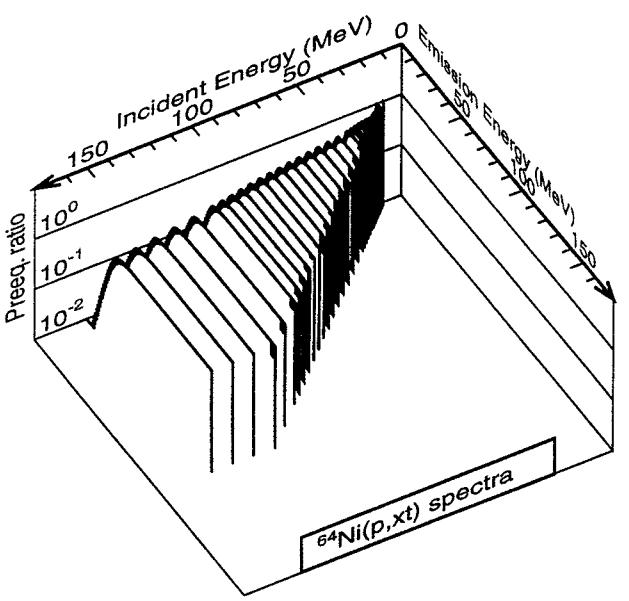


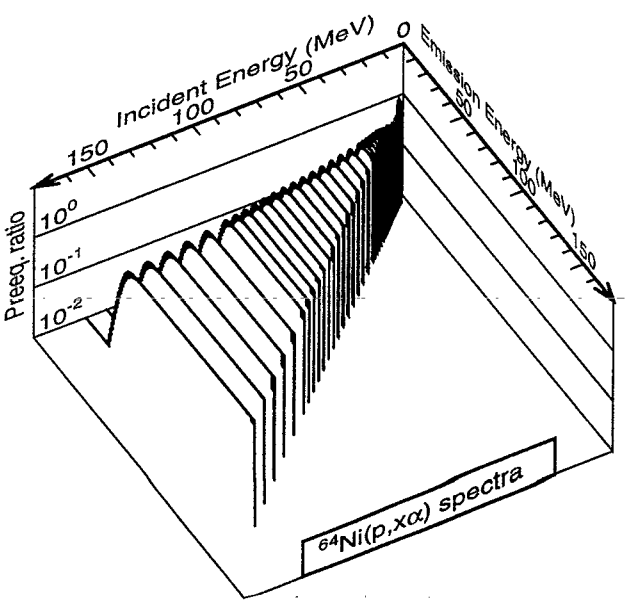
p + ^{64}Ni Kalbach preequilibrium ratios

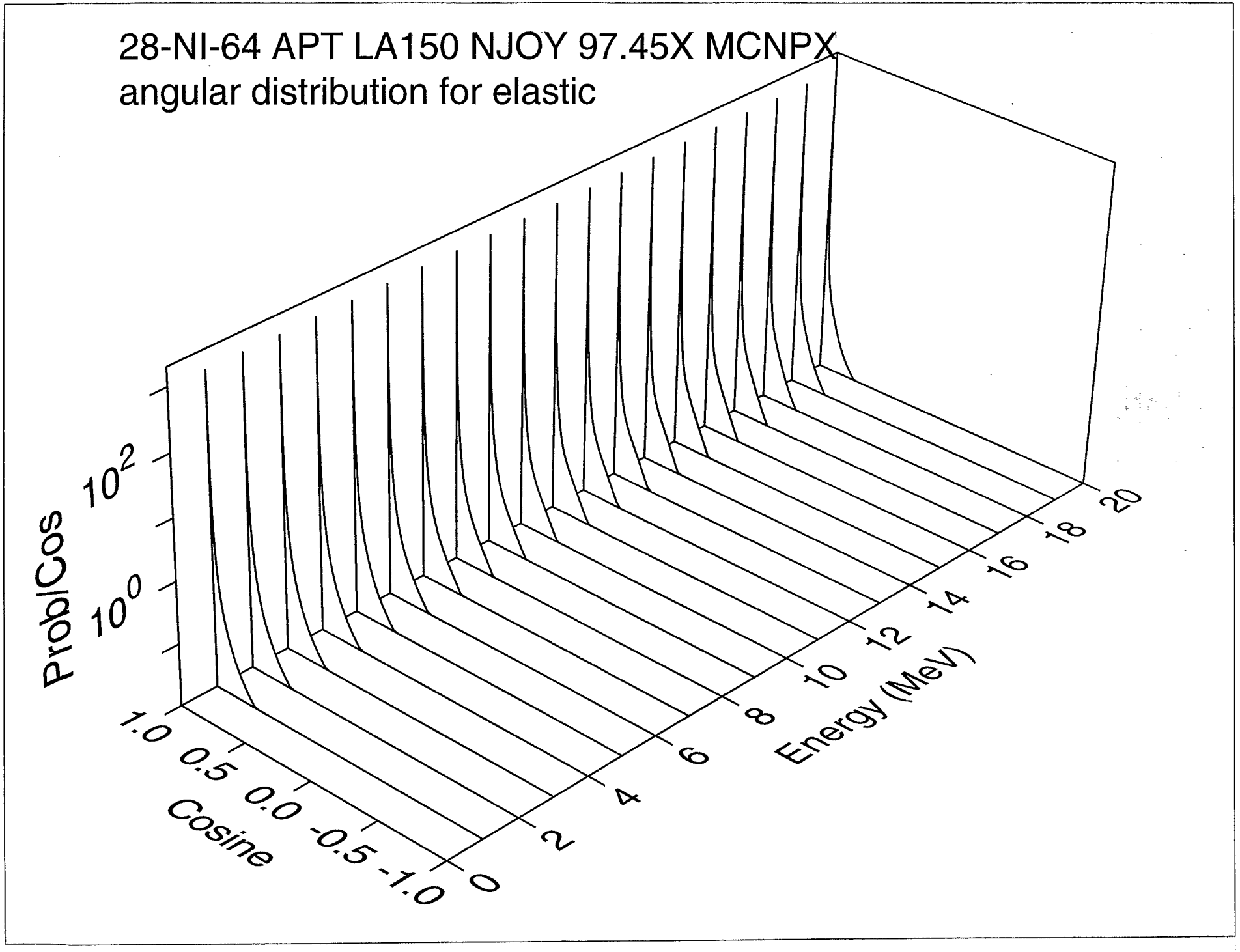


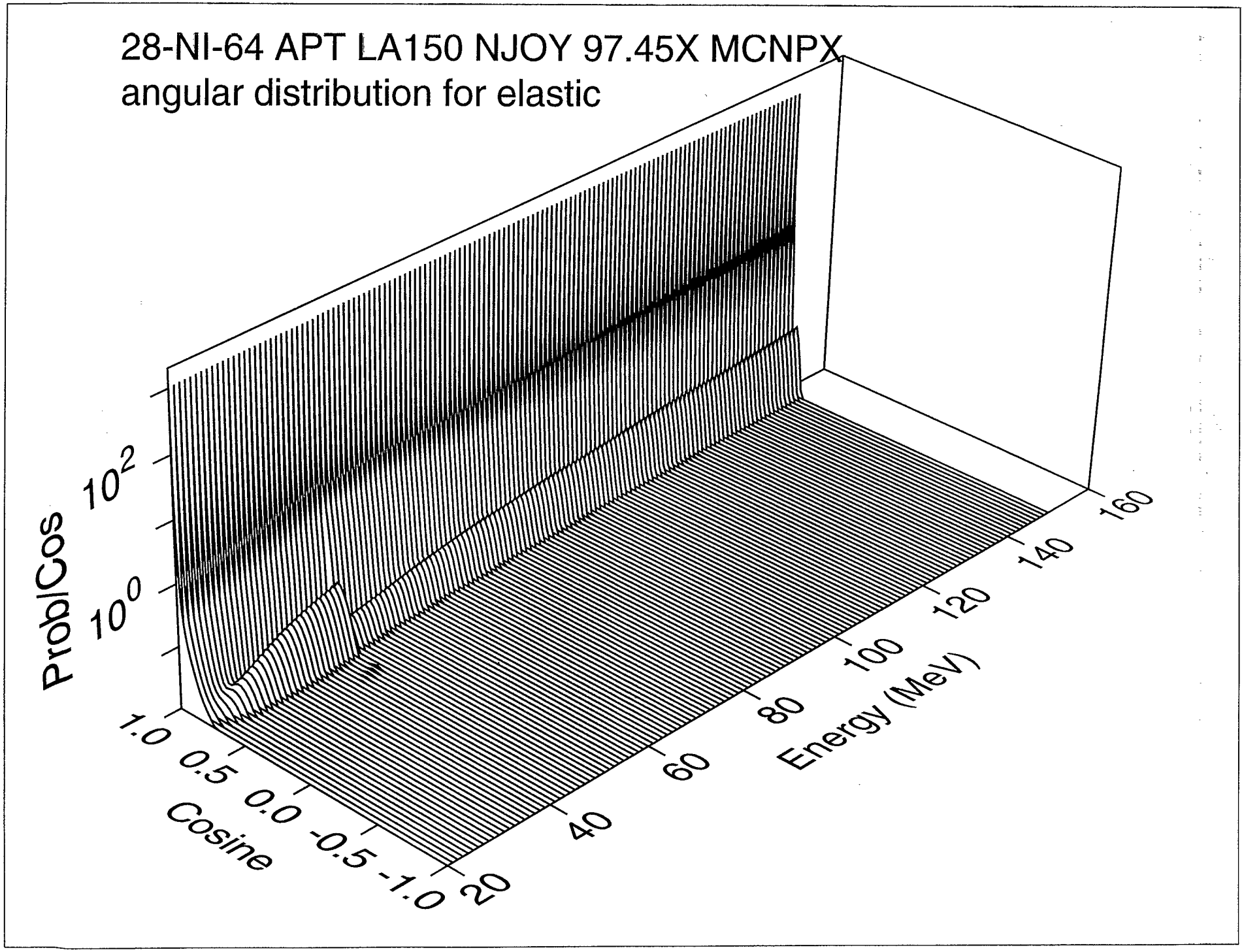


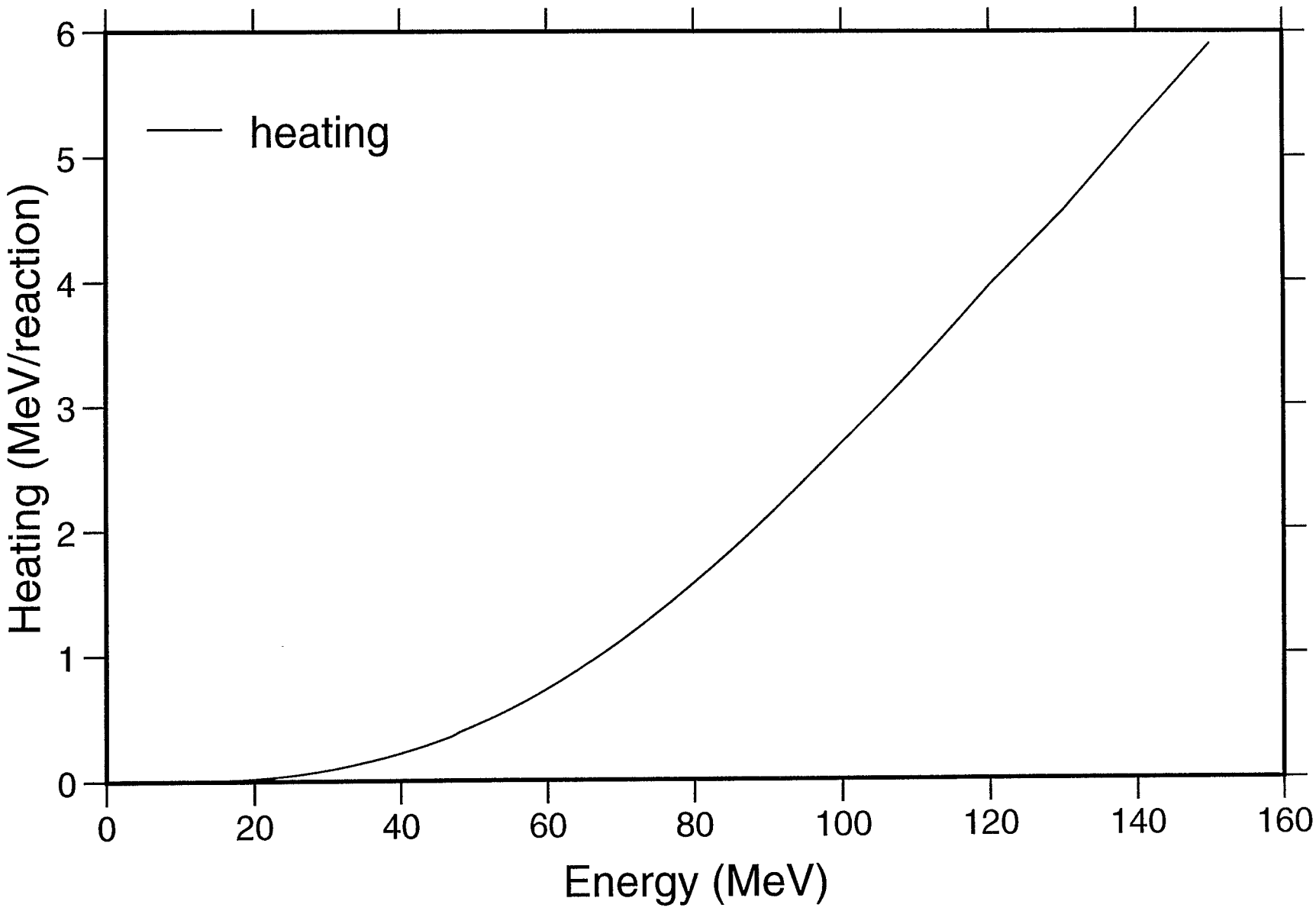







28-NI-64 APT LA150 NJOY 97.45X MCNPX
angular distribution for elastic
Prob/Cos
10^2
10^0
1.0
0.5
0.0
-0.5
-1.0
Cosine
0
2
4
6
8
10
12
14
16
18
20
Energy (MeV)


28-NI-64 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-64 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