EVALUATION OF p + 28Si CROSS SECTIONS FOR THE ENERGY RANGE 1 to 150 MeV

M. B. Chadwick and P. G. Young
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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 + Si28 and p + Si28 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 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 below. Gamma-ray transmission

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

DETAILS OF THE p + SI-28 ANALYSIS

The Madland global medium-energy optical potential (Ma88) was used for neutrons above 46 MeV, and the Wilmore-Hodgson potential was used for lower neutron energies. The Madland global medium-energy optical potential was used for protons above 28 MeV, and the Beccheti-Greenlees potential was used for lower proton energies. In both cases the transition region to the Madland potential was chosen to approximately give continuity in the reaction cross section. For deuterons, the Perey global potential was used; for alpha particles the Moyen potential was used; and for tritons the Beccheti-Greenlees potential was used.

While the above optical potentials did describe the experimental proton nonelastic cross section data fairly well, we modified the theoretical predictions slightly to better agree with the measurements, and renormalized the transmission coefficients accordingly. In addition to using Si nonelastic proton cross section measurements, we also were guided by p+Al nonelastic data, scaled by A**2/3.

Coupled-channel optical model calculations were performed to determine inelastic scattering on 28Si, for the 0+, 2+, and 4+ states, as well as a DWBA calculation of the inelastic scattering to the 3- vibrational state, all performed with the ECIS code. Near 20 MeV neutron energy, neutron inelastic scattering to these states has been measured by Alarcon and Rapaport, and Finlay et al., from Ohio University, and the inelastic cross sections to these collective states is in good agreement with the ORNL ENDF evaluation for 28Si. We performed a rotational band (0+, 2+, 4+) coupled channel calculation using the Madland medium energy potential at higher energies and Beccheti-Greenlees at lower energies (with their imaginary potentials reduced by 20%, to approximately account for the coupling). Deformation parameters were chosen to reproduce the ENDF/B-VI neutron cross sections at 20 MeV, resulting in values of beta-2=-0.365, beta-4=+0.22, in good agreement with Rapaport's values of -0.37, 0.17 respectively. A vibrational DWBA calculation (using ECIS) was performed for the 3- state resulting in beta-3=0.235 (Rapaport obtained 0.23). These same beta values were used for the proton-inelastic scattering calculations.

The calculated emission spectra were indirectly benchmarked by comparing neutron-induced calculations with neutron-induced data. Only 2 measurements exist for neutron-induced emission spectra above 20 MeV for 28Si. New data have been published by the Louvain group at the 1997 Trieste conference for 63 MeV Si(n,xz) double-differential spectra (z=p,d,a ejectiles). Additionally, Haight et al. of Los Alamos have preliminary data for Si(n,xp), for neutrons up to 50 MeV, including emission spectra at four angles. Our calculations agree reasonably well with these measurements. While default level density parameters (using the Ignatyuk model) were utilized, in the case of 28Al the level density parameter was slightly modified to optimize agreement with the Abfalterer total level density measurements based on fluctuation analyses (Ab93).

As an independent validation of our GNASH calculations using the exciton model, we have also performed FKK calculations. This was done by implementing a multistep reaction theory recently

developed by Koning and Chadwick, which is particularly suited to the simultaneous calculation of neutron and proton emission. The FKK theory describes the forward-peaking very well, as do our exciton model calculations using the phenomenological Kalbach angular distribution systematics.

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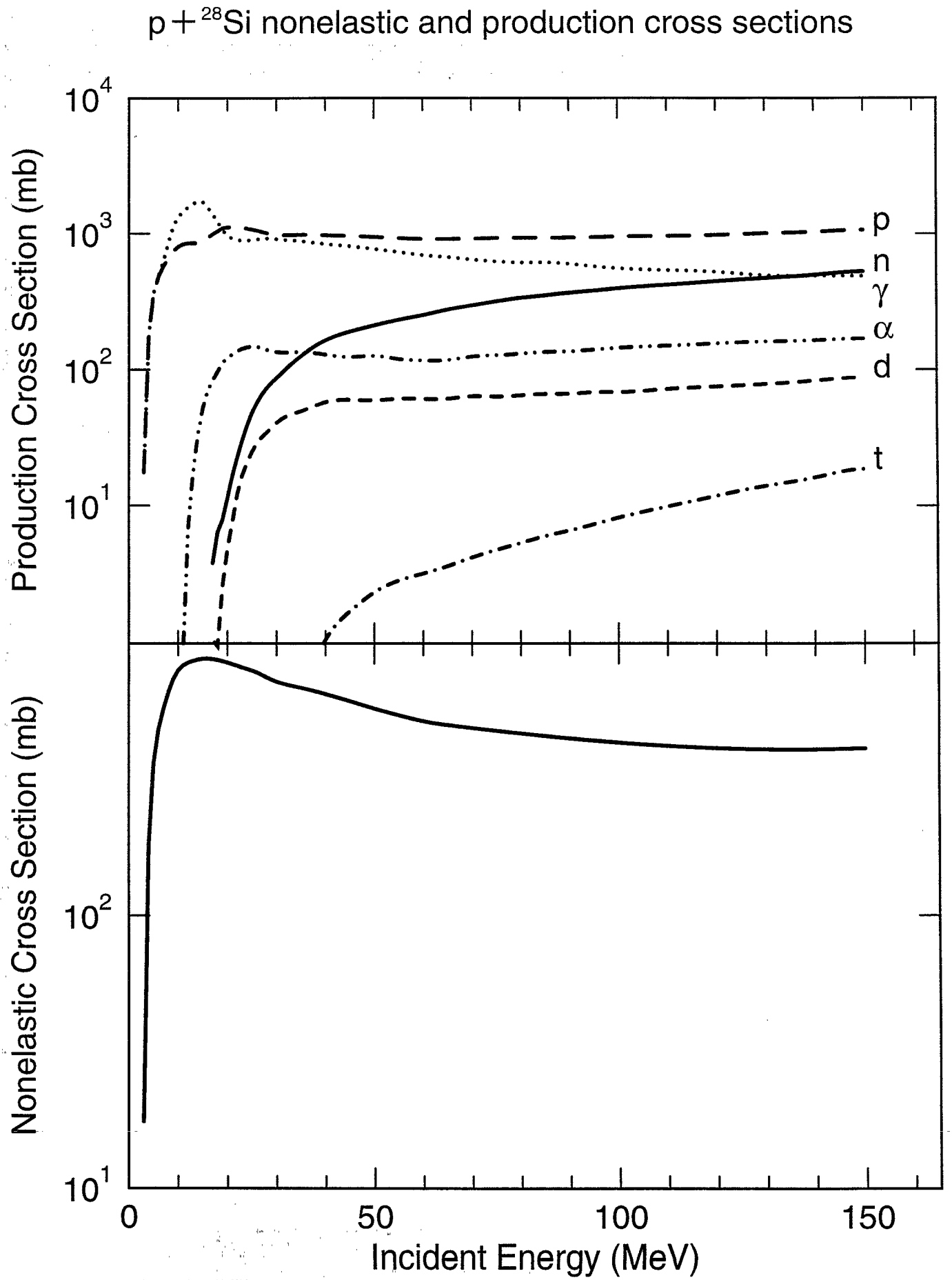
14028 = TARGET 1000Z+A (if A=0 then elemental)
1001 = PROJECTILE 1000Z+A
Nonelastic, elastic, and Production cross sections for A<5 ejectiles in barns:

Energy	nonelas	elastic	neutron	proton	deuteron	triton	helium3	alpha	gamma
3.000E+00	1.751E-02	0.000E+00	0.000E+00	1.751E-02	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1.751E-02
4.000E+00	1.813E-01	0.000E+00	0.000E+00	1.813E-01	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1.813E-01
5.000E+00	3.639E-01	0.000E+00	0.000E+00	3.639E-01	0.000E+00	0.000E+00	0.000E+00	0.000E+00	3.639E-01
6.000E+00	4.831E-01	0.000E+00	0.000E+00	4.831E-01	0.000E+00	0.000E+00	0.000E+00	0.000E+00	4.855E-01
7.000E+00	5.731E-01	0.000E+00	0.000E+00	5.731E-01	0.000E+00	0.000E+00	0.000E+00	0.000E+00	6.268E-01
8.000E+00	6.603E-01	0.000E+00	0.000E+00	6.603E-01	0.000E+00	0.000E+00	0.000E+00	0.000E+00	8.494E-01
9.000E+00	7.421E-01	0.000E+00	0.000E+00	7.421E-01	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1.127E+00
1.000E+01	7.967E-01	0.000E+00	0.000E+00	7.966E-01	0.000E+00	0.000E+00	0.000E+00	1.264E-05	1.318E+00
1.100E+01	8.319E-01	0.000E+00	0.000E+00	8.311E-01	0.000E+00	0.000E+00	0.000E+00	7.743E-04	1.452E+00
1.200E+01	8.507E-01	0.000E+00	0.000E+00	8.438E-01	0.000E+00	0.000E+00	0.000E+00	6.848E-03	1.556E+00
1.300E+01	8.632E-01	0.000E+00	0.000E+00	8.460E-01	0.000E+00	0.000E+00	0.000E+00	1.748E-02	1.651E+00
1.400E+01	8.723E-01	0.000E+00	0.000E+00	8.448E-01	0.000E+00	0.000E+00	0.000E+00	3.345E-02	1.716E+00
1.500E+01	8.779E-01	0.000E+00	0.000E+00	8.671E-01	0.000E+00	0.000E+00	0.000E+00	5.230E-02	1.704E+00
1.600E+01	8.786E-01	0.000E+00	1.641E-03	9.231E-01	6.560E-10	0.000E+00	0.000E+00	6.989E-02	1.564E+00
1.700E+01	8.752E-01	0.000E+00	3.818E-03	9.867E-01	9.884E-05	0.000E+00	0.000E+00	8.364E-02	1.383E+00
1.800E+01	8.689E-01	0.000E+00	6.367E-03	1.037E+00	9.545E-04	0.000E+00	0.000E+00	9.655E-02	1.222E+00
1.900E+01	8.601E-01	0.000E+00	7.874E-03	1.092E+00	2.592E-03	0.000E+00	0.000E+00	1.120E-01	1.062E+00
2.000E+01	8.501E-01	0.000E+00	1.130E-02	1.107E+00	4.799E-03	0.000E+00	0.000E+00	1.216E-01	9.622E-01
2.200E+01	8.279E-01	0.000E+00	2.254E-02	1.108E+00	1.201E-02	0.000E+00	0.000E+00	1.369E-01	8.918E-01
2.400E+01	8.053E-01	0.000E+00	3.867E-02	1.085E+00	2.061E-02	2.034E-07	0.000E+00	1.453E-01	8.829E-01
2.600E+01	7.822E-01	0.000E+00	5.673E-02	1.050E+00	2.879E-02	1.175E-05	0.000E+00	1.470E-01	8.991E-01
2.800E+01	7.502E-01	0.000E+00	7.280E-02	1.004E+00	3.432E-02	5.065E-05	0.000E+00	1.392E-01	9.149E-01
3.000E+01	7.240E-01	0.000E+00	8.655E-02	9.758E-01	4.049E-02	1.166E-04	0.000E+00	1.342E-01	9.041E-01
3.500E+01	6.860E-01	0.000E+00	1.256E-01	9.764E-01	4.918E-02	4.319E-04	0.000E+00	1.344E-01	8.748E-01
4.000E+01	6.503E-01	0.000E+00	1.639E-01	9.705E-01	5.773E-02	1.063E-03	0.000E+00	1.290E-01	8.343E-01
4.500E+01	6.126E-01	0.000E+00	1.905E-01	9.589E-01	6.005E-02	1.710E-03	0.000E+00	1.239E-01	8.043E-01
5.000E+01	5.753E-01	0.000E+00	2.117E-01	9.420E-01	5.956E-02	2.347E-03	0.000E+00	1.262E-01	7.682E-01
5.500E+01	5.437E-01	0.000E+00	2.327E-01	9.239E-01	6.103E-02	2.853E-03	0.000E+00	1.196E-01	7.313E-01
6.000E+01	5.171E-01	0.000E+00	2.522E-01	9.105E-01	6.084E-02	3.208E-03	0.000E+00	1.166E-01	6.934E-01
6.500E+01	5.007E-01	0.000E+00	2.768E-01	9.096E-01	6.108E-02	3.635E-03	0.000E+00	1.175E-01	6.714E-01
7.000E+01	4.882E-01	0.000E+00	2.972E-01	9.161E-01	6.366E-02	4.184E-03	0.000E+00	1.247E-01	6.442E-01
7.500E+01	4.764E-01	0.000E+00	3.181E-01	9.268E-01	6.322E-02	4.761E-03	0.000E+00	1.277E-01	6.240E-01
8.000E+01	4.656E-01	0.000E+00	3.369E-01	9.292E-01	6.458E-02	5.337E-03	0.000E+00	1.309E-01	6.112E-01
8.500E+01	4.555E-01	0.000E+00	3.509E-01	9.287E-01	6.609E-02	5.991E-03	0.000E+00	1.347E-01	6.123E-01
9.000E+01	4.464E-01	0.000E+00	3.670E-01	9.322E-01	6.630E-02	6.574E-03	0.000E+00	1.360E-01	5.978E-01
9.500E+01	4.383E-01	0.000E+00	3.800E-01	9.395E-01	6.805E-02	7.318E-03	0.000E+00	1.400E-01	5.733E-01
1.000E+02	4.311E-01	0.000E+00	3.953E-01	9.506E-01	6.821E-02	8.175E-03	0.000E+00	1.441E-01	5.542E-01
1.100E+02	4.194E-01	0.000E+00	4.196E-01	9.589E-01	7.191E-02	9.850E-03	0.000E+00	1.493E-01	5.352E-01
1.200E+02	4.112E-01	0.000E+00	4.453E-01	9.756E-01	7.501E-02	1.181E-02	0.000E+00	1.551E-01	5.207E-01
1.300E+02	4.070E-01	0.000E+00	4.704E-01	1.004E+00	7.822E-02	1.395E-02	0.000E+00	1.604E-01	4.903E-01
1.400E+02	4.068E-01	0.000E+00	4.955E-01	1.030E+00	8.302E-02	1.612E-02	0.000E+00	1.640E-01	4.880E-01
1.500E+02	4.102E-01	0.000E+00	5.248E-01	1.066E+00	8.761E-02	1.858E-02	0.000E+00	1.689E-01	4.873E-01

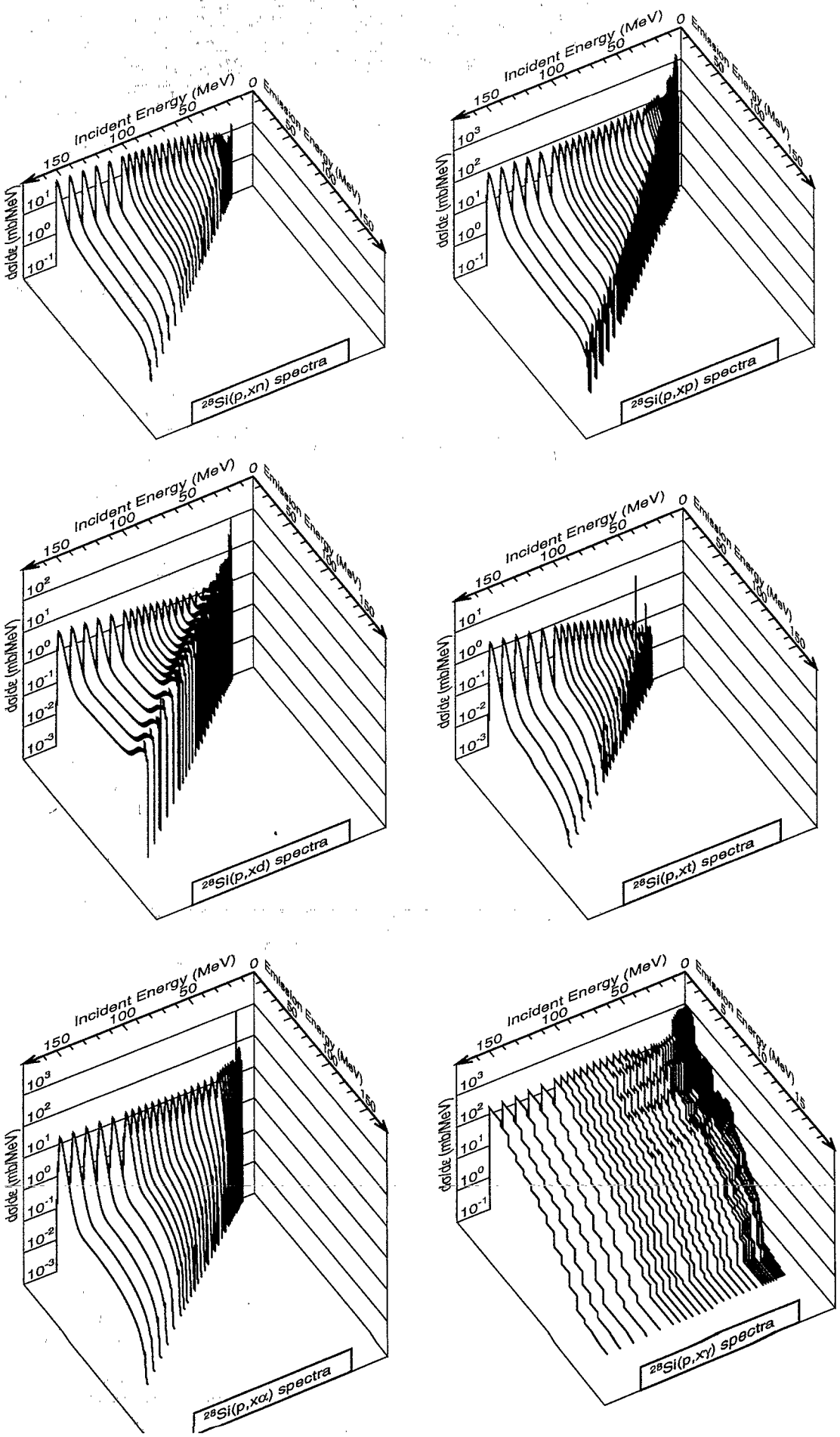
14028 = TARGET 1000Z+A (if A=0 then elemental)
1001 = PROJECTILE 1000Z+A
Aver. lab emission energies for A<5 ejectiles in MeV:

Energy	neutron	proton	deuteron	triton	helium3	alpha	gamma
3.000E+00	0.000E+00	9.689E-01	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1.750E+00
4.000E+00	0.000E+00	1.936E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1.750E+00
5.000E+00	0.000E+00	2.903E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1.750E+00
6.000E+00	0.000E+00	3.858E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1.755E+00
7.000E+00	0.000E+00	4.574E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1.852E+00
8.000E+00	0.000E+00	4.887E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	2.075E+00
9.000E+00	0.000E+00	4.740E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	2.514E+00
1.000E+01	0.000E+00	4.739E+00	0.000E+00	0.000E+00	0.000E+00	1.623E+00	2.841E+00
1.100E+01	0.000E+00	4.764E+00	0.000E+00	0.000E+00	0.000E+00	2.505E+00	3.174E+00
1.200E+01	0.000E+00	4.998E+00	0.000E+00	0.000E+00	0.000E+00	3.222E+00	3.377E+00
1.300E+01	0.000E+00	5.332E+00	0.000E+00	0.000E+00	0.000E+00	3.916E+00	3.516E+00
1.400E+01	0.000E+00	5.727E+00	0.000E+00	0.000E+00	0.000E+00	4.069E+00	3.616E+00
1.500E+01	0.000E+00	5.999E+00	0.000E+00	0.000E+00	0.000E+00	3.890E+00	3.657E+00
1.600E+01	1.784E-01	6.104E+00	4.409E-01	0.000E+00	0.000E+00	3.823E+00	3.655E+00
1.700E+01	9.800E-01	6.215E+00	1.364E+00	0.000E+00	0.000E+00	3.903E+00	3.611E+00
1.800E+01	1.416E+00	6.392E+00	2.140E+00	0.000E+00	0.000E+00	4.043E+00	3.509E+00
1.900E+01	1.686E+00	6.490E+00	2.804E+00	0.000E+00	0.000E+00	3.990E+00	3.387E+00
2.000E+01	2.072E+00	6.772E+00	3.111E+00	0.000E+00	0.000E+00	4.374E+00	3.384E+00
2.200E+01	2.561E+00	7.479E+00	4.417E+00	0.000E+00	0.000E+00	4.914E+00	3.113E+00
2.400E+01	3.037E+00	8.106E+00	5.578E+00	9.749E-01	0.000E+00	5.306E+00	2.933E+00
2.600E+01	3.577E+00	8.763E+00	6.714E+00	2.713E+00	0.000E+00	5.627E+00	2.848E+00
2.800E+01	4.162E+00	9.399E+00	7.888E+00	3.473E+00	0.000E+00	6.119E+00	2.853E+00
3.000E+01	4.726E+00	9.988E+00	9.073E+00	4.360E+00	0.000E+00	6.493E+00	2.869E+00
3.500E+01	5.889E+00	1.073E+01	1.192E+01	6.596E+00	0.000E+00	7.135E+00	2.797E+00

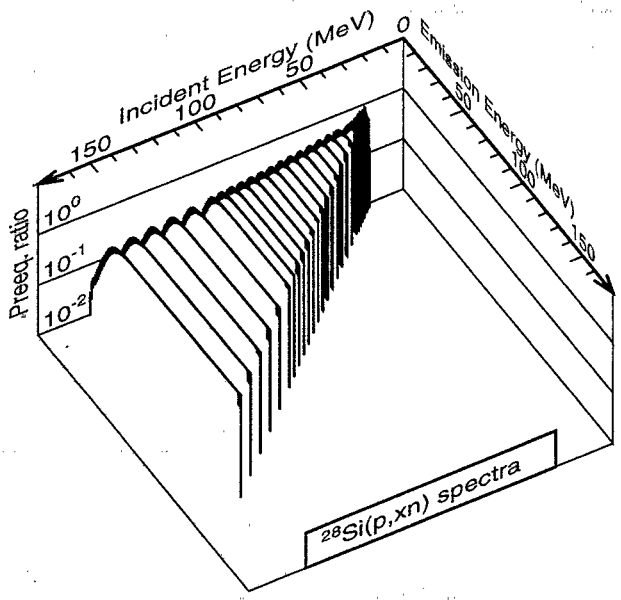
4.000E+01	7.028E+00	1.158E+01	1.509E+01	7.613E+00	0.000E+00	7.487E+00	2.573E+00
4.500E+01	8.162E+00	1.239E+01	1.813E+01	8.612E+00	0.000E+00	7.898E+00	2.412E+00
5.000E+01	9.133E+00	1.307E+01	2.119E+01	9.517E+00	0.000E+00	8.335E+00	2.330E+00
5.500E+01	1.010E+01	1.388E+01	2.434E+01	1.051E+01	0.000E+00	8.632E+00	2.277E+00
6.000E+01	1.095E+01	1.469E+01	2.711E+01	1.141E+01	0.000E+00	8.937E+00	2.225E+00
6.500E+01	1.167E+01	1.550E+01	2.985E+01	1.214E+01	0.000E+00	9.166E+00	2.208E+00
7.000E+01	1.234E+01	1.604E+01	3.254E+01	1.245E+01	0.000E+00	9.322E+00	2.168E+00
7.500E+01	1.305E+01	1.672E+01	3.455E+01	1.271E+01	0.000E+00	9.454E+00	2.151E+00
8.000E+01	1.375E+01	1.739E+01	3.686E+01	1.278E+01	0.000E+00	9.598E+00	2.115E+00
8.500E+01	1.456E+01	1.813E+01	3.897E+01	1.282E+01	0.000E+00	9.724E+00	2.129E+00
9.000E+01	1.540E+01	1.886E+01	4.059E+01	1.292E+01	0.000E+00	9.797E+00	2.129E+00
9.500E+01	1.612E+01	1.949E+01	4.259E+01	1.279E+01	0.000E+00	9.871E+00	2.086E+00
1.000E+02	1.681E+01	2.011E+01	4.359E+01	1.256E+01	0.000E+00	9.940E+00	2.073E+00
1.100E+02	1.823E+01	2.144E+01	4.687E+01	1.214E+01	0.000E+00	1.017E+01	2.074E+00
1.200E+02	1.964E+01	2.268E+01	4.889E+01	1.177E+01	0.000E+00	1.039E+01	2.104E+00
1.300E+02	2.101E+01	2.390E+01	5.059E+01	1.145E+01	0.000E+00	1.059E+01	2.070E+00
1.400E+02	2.239E+01	2.520E+01	5.296E+01	1.122E+01	0.000E+00	1.084E+01	2.083E+00
1.500E+02	2.378E+01	2.643E+01	5.419E+01	1.106E+01	0.000E+00	1.107E+01	2.116E+00

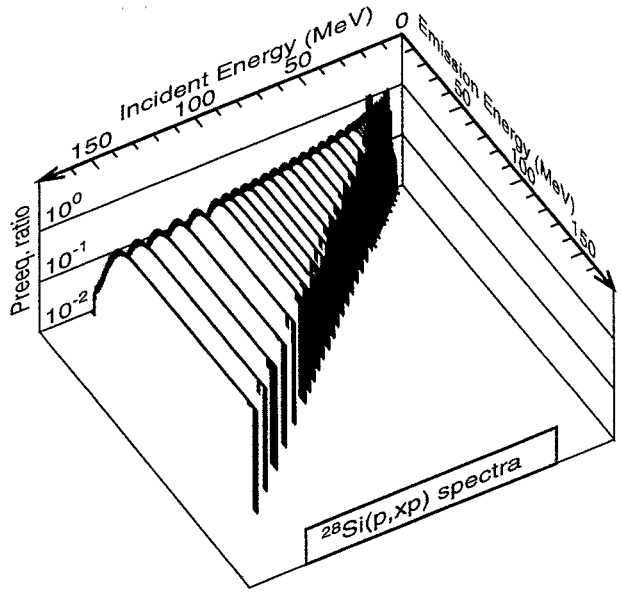

p + 28Si nonelastic and production cross sections
Production Cross Section (mb)
10^4
10^3
10^2
10^1
p
n
γ
α
d
t
Nonelastic Cross Section (mb)
10^2
10^1
0
50
100
150
Incident Energy (MeV)

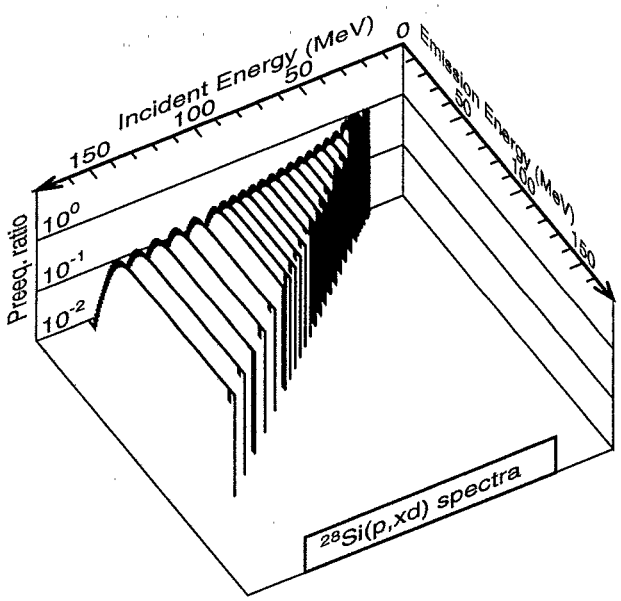
p + ^{28}Si angle-integrated emission spectra

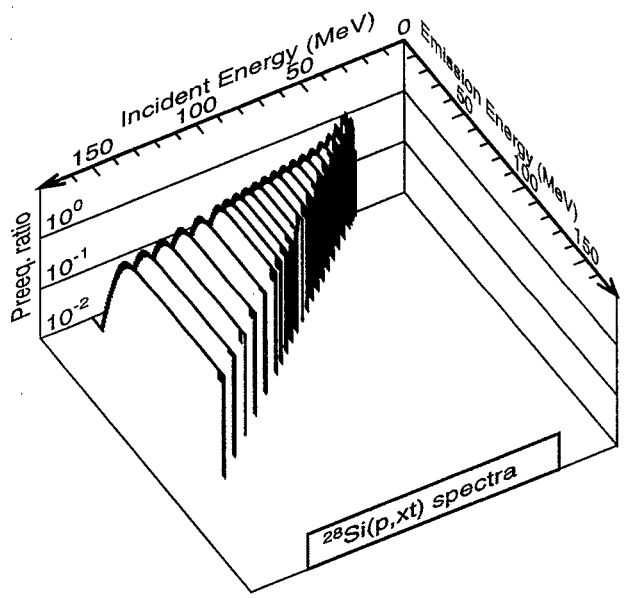


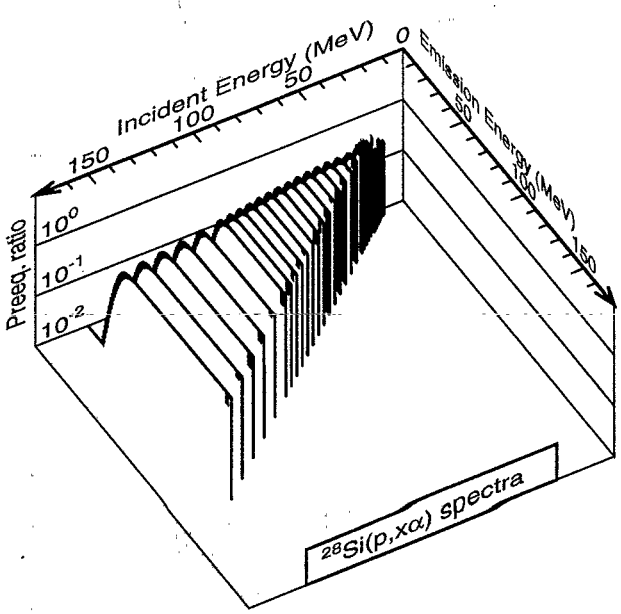
p + ^{28}Si Kalbach preequilibrium ratios

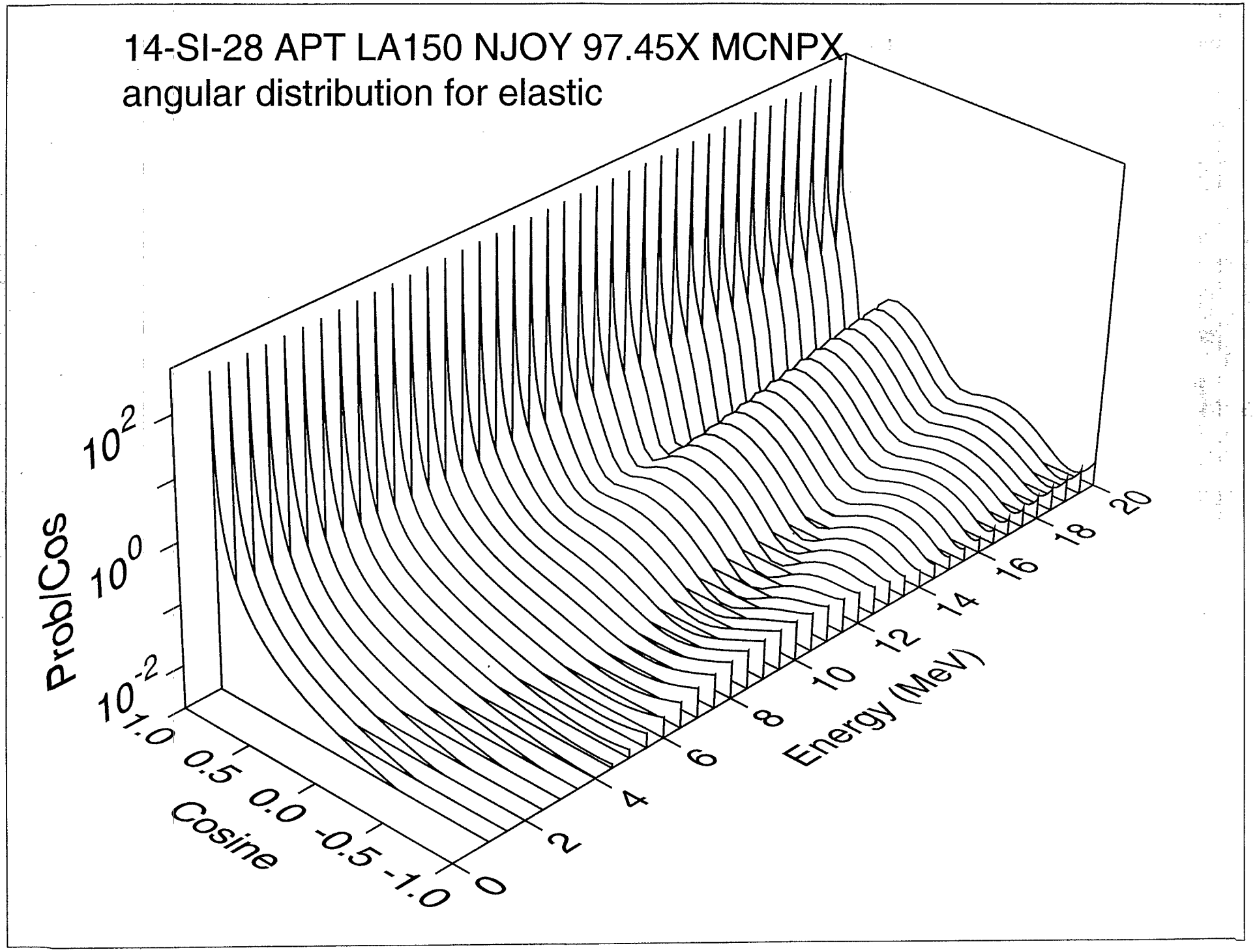


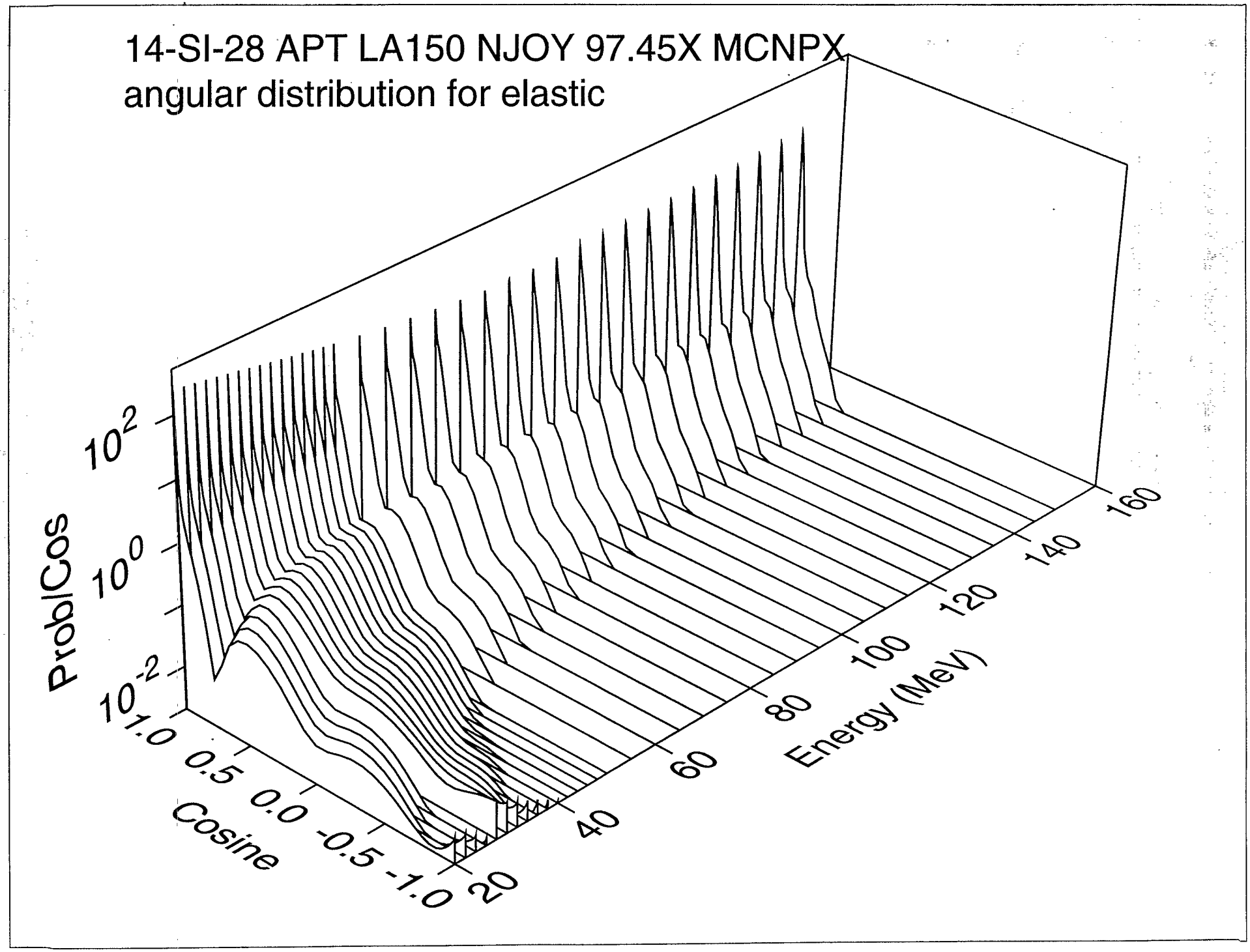


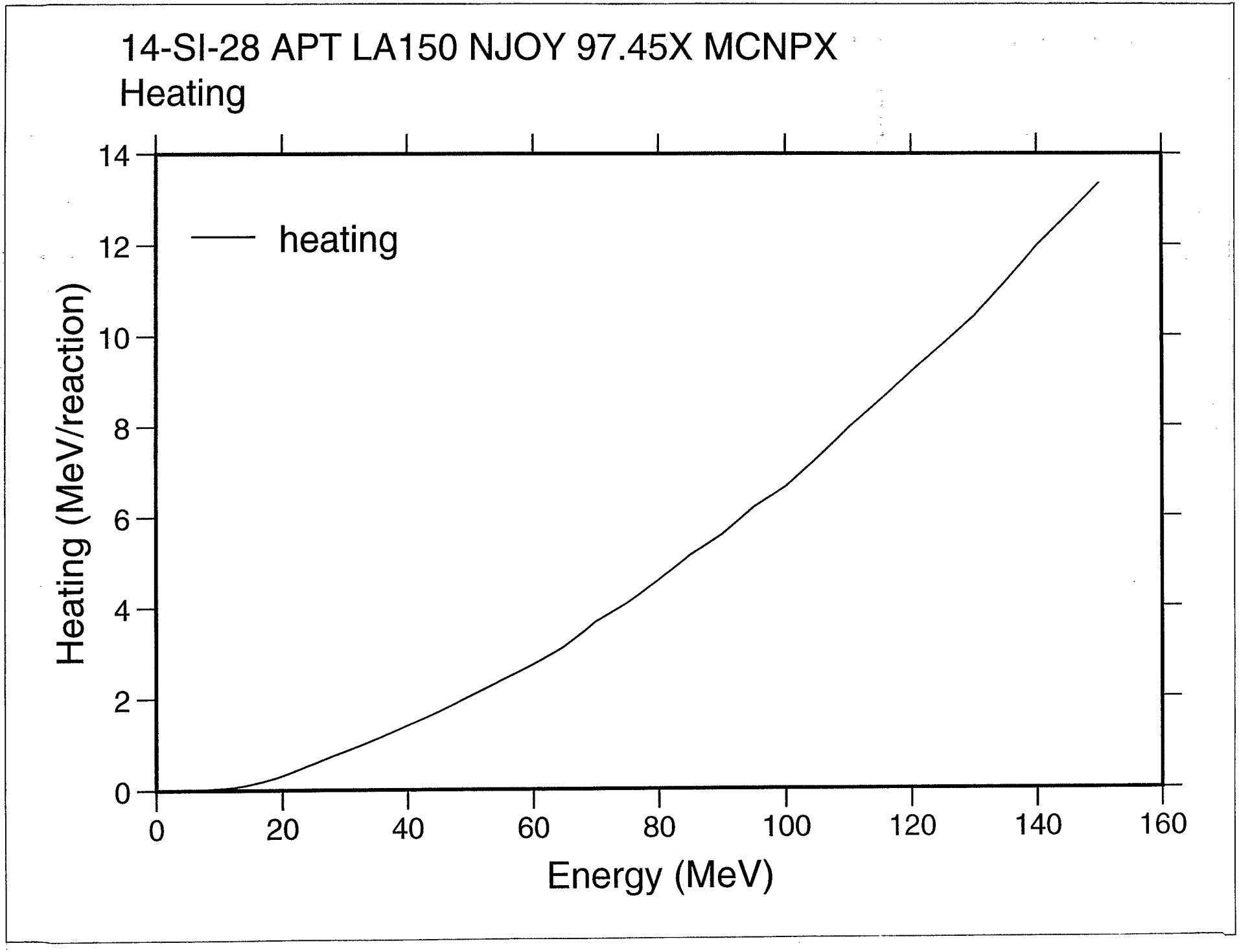







14-SI-28 APT LA150 NJOY 97.45X MCNPX
angular distribution for elastic
ProblCos
10^2
10^0
10^{-2}
Cosine
1.0
0.5
0.0
-0.5
-1.0
Energy (MeV)
0
2
4
6
8
10
12
14
16
18
20


14-SI-28 APT LA150 NJOY 97.45X MCNPX
angular distribution for elastic
ProblCos
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


14-SI-28 APT LA150 NJOY 97.45X MCNPX
Heating
heating
Heating (MeV/reaction)
Energy (MeV)
0
2
4
6
8
10
12
14
0
20
40
60
80
100
120
140
160