EVALUATION OF n + 93Nb 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 +93Nb and n +93Nb 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 NB-93 EVALUATION

The total neutron cross section was obtained from the Finlay(Fi93) measurements.

The following optical potentials were used in the GNASH calculations. For incident neutrons, the Wilmore-Hodgson potential was used below 15 MeV, and the Madland potential (Ma88) was used at higher energies. For incident protons, the Becchetti-Greenlees (Be69) potential was used up to 50 MeV, above which the Madland potential (Ma88) was used. In both cases, the matching energy between the potentials was chosen to result in continuity of the reaction cross section. For protons at 50 MeV the reaction cross section (and transmission coefficients) was renormalized slightly to smoothen the transition between the potentials. The Perey (Pe63) potential was used for indident deuterons. For tritons, the Becchetti-Greenlees (Be71) was used up to 80 MeV, above which the Watanabe potential was used. The Moyen (McFadden Satchler) (Mc66) potential was used for alpha particles over the whole energy range.

Direct inelastic scattering to low-lying states in Nb93 was determined as follows. Coherent excitation of 2+ and 3- vibrations were assumed to be fragmented over Nb93 states, after coupling these excitations with the 4.5+ core. The magnitudes of the deformation lengths of 2+ and 3- excitations was obtained by fitting values of 34 and 46 mb respectively at 14 MeV, obtained in ref. (Ch93) and accounting for measurements well. This strength was then fragmented over Nb states. For the 3- excitation, the 7 states are in the "continuum" region of the GNASH calculation at approximately 2.5 MeV, with spins 1.5-,2.5-, ..,7.5-. For the 2+, the 5 states (2.5+,3.5+,...6.5+) near 1 MeV were assumed to be those whose inelastic cross section in the existing ENDF <20 MeV file are significant (note that the ENDF file below 20 MeV appears to incorporate inelastic information only up to 5 MeV for many states, after which a value of zero at 20 MeV was inserted).

Experimental data is used to benchmark the calculations. For incident neutrons, experimental neutron emission spectra data exist at 20 and 26 MeV by Marcinkowski (Ma83). For incident protons, spectra data exist at 14 and 26 MeV by Watanabe et al. (Wa97), and at 65 MeV by Sakai et al (Sa80). Our evaluation agrees reasonably well with these measurements.

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REFERENCES

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

[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.

[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.

[Ch98]. M. B. Chadwick and P. G. Young, "Model Calculations of n,p + 93Nb" in APT PROGRESS REPORT: 1 November 1997 - 1 January 1998, internal Los Alamos National Laboratory memo 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).

[Fi93]. R. W. Finlay, W. P. Abfalterer, G. Fink, E. Montei, T. Adami, P. W. Lisowski, G. L. Morgan, and R. C. Haight, Phys. Rev. C 47, 237 (1993).

[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).

[Ma83]. A. Marcinkowski, Nucl. Phys. A402, 220 (1983).

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

[Pe63]. C. M. Perey and F. G. Perey, Phys. Rev. 132, 755 (1963).

[Sa80]. H. Sakai et al., Nucl. Phys. A344, 41 (1980)

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

[Wa97] Y. Watanabe et al, Proc. of International Conference on Nucl. Data for Sci and Tech, Trieste, May 19-24 (1997) Ed. G. Reffo (in press).

[Wi64]. D. Wilmore and P. E. Hodgson, Nucl. Phys. 55, 673 (1964)

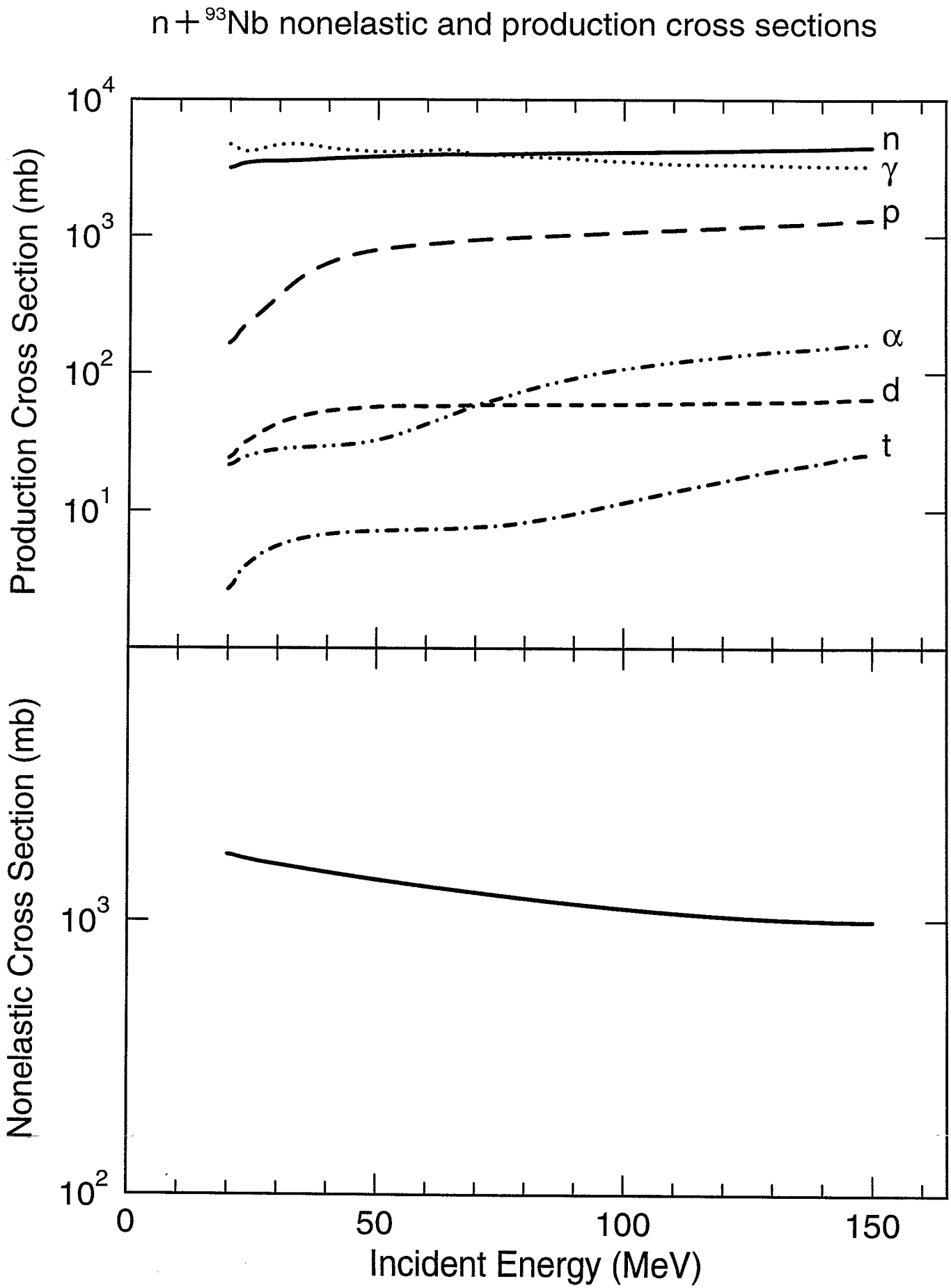
[Yo92]. P. G. Young, E. D. Arthur, and M. B. Chadwick, "Comprehensive Nuclear Model Calculations: Introduction to the Theory and Use of the GNASH Code," LA-12343-MS (1992).

41093 = TARGET 1000Z+A (if A=0 then elemental)
1 = PROJECTILE 1000Z+A
Nonelastic, elastic, and Production cross sections for A<5 ejectiles in barns:

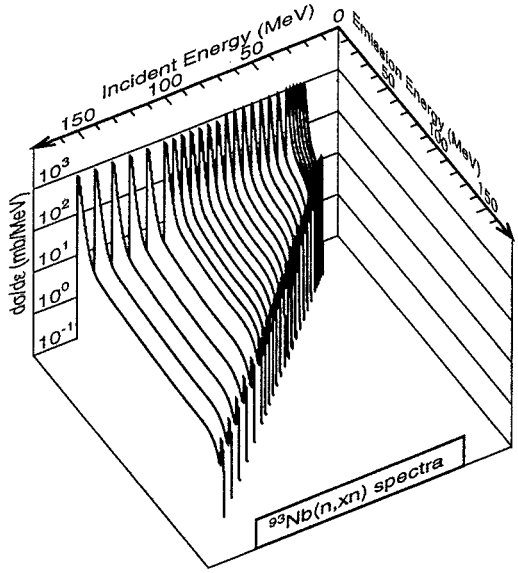
Energy	nonelas	elastic	neutron	proton	deuteron	triton	helium3	alpha	gamma
2.000E+01	1.741E+00	1.614E+00	3.165E+00	1.649E-01	2.419E-02	2.673E-03	0.000E+00	2.138E-02	4.697E+00
2.200E+01	1.708E+00	1.472E+00	3.347E+00	1.992E-01	2.859E-02	3.432E-03	0.000E+00	2.339E-02	4.269E+00
2.400E+01	1.675E+00	1.384E+00	3.466E+00	2.338E-01	3.254E-02	4.109E-03	0.000E+00	2.502E-02	4.190E+00
2.600E+01	1.644E+00	1.316E+00	3.525E+00	2.700E-01	3.620E-02	4.686E-03	0.000E+00	2.626E-02	4.318E+00
2.800E+01	1.620E+00	1.260E+00	3.548E+00	3.113E-01	3.978E-02	5.174E-03	0.000E+00	2.725E-02	4.523E+00
3.000E+01	1.599E+00	1.252E+00	3.555E+00	3.640E-01	4.312E-02	5.579E-03	0.000E+00	2.794E-02	4.667E+00
3.500E+01	1.545E+00	1.331E+00	3.594E+00	5.107E-01	4.916E-02	6.319E-03	0.000E+00	2.883E-02	4.695E+00
4.000E+01	1.494E+00	1.466E+00	3.678E+00	6.320E-01	5.320E-02	6.776E-03	0.000E+00	2.948E-02	4.399E+00
4.500E+01	1.449E+00	1.615E+00	3.742E+00	7.247E-01	5.537E-02	7.035E-03	0.000E+00	3.052E-02	4.225E+00
5.000E+01	1.406E+00	1.743E+00	3.806E+00	7.881E-01	5.708E-02	7.171E-03	0.000E+00	3.272E-02	4.138E+00
5.500E+01	1.367E+00	1.839E+00	3.874E+00	8.332E-01	5.791E-02	7.274E-03	0.000E+00	3.680E-02	4.162E+00
6.000E+01	1.330E+00	1.885E+00	3.933E+00	8.691E-01	5.768E-02	7.352E-03	0.000E+00	4.272E-02	4.218E+00
6.500E+01	1.296E+00	1.929E+00	3.971E+00	9.009E-01	5.807E-02	7.445E-03	0.000E+00	4.990E-02	4.283E+00
7.000E+01	1.263E+00	1.911E+00	3.955E+00	9.375E-01	5.895E-02	7.643E-03	0.000E+00	5.856E-02	3.967E+00
7.500E+01	1.232E+00	1.886E+00	3.978E+00	9.610E-01	5.921E-02	7.851E-03	0.000E+00	6.621E-02	3.912E+00
8.000E+01	1.202E+00	1.838E+00	4.009E+00	9.844E-01	5.927E-02	8.266E-03	0.000E+00	7.503E-02	3.808E+00
8.500E+01	1.175E+00	1.790E+00	4.042E+00	1.004E+00	5.928E-02	8.843E-03	0.000E+00	8.392E-02	3.749E+00
9.000E+01	1.150E+00	1.730E+00	4.068E+00	1.023E+00	5.935E-02	9.564E-03	0.000E+00	9.219E-02	3.687E+00
9.500E+01	1.126E+00	1.644E+00	4.089E+00	1.046E+00	5.955E-02	1.052E-02	0.000E+00	1.007E-01	3.585E+00
1.000E+02	1.104E+00	1.579E+00	4.109E+00	1.066E+00	5.979E-02	1.151E-02	0.000E+00	1.077E-01	3.520E+00
1.100E+02	1.066E+00	1.424E+00	4.156E+00	1.109E+00	6.055E-02	1.388E-02	0.000E+00	1.209E-01	3.377E+00
1.200E+02	1.036E+00	1.284E+00	4.205E+00	1.153E+00	6.144E-02	1.653E-02	0.000E+00	1.324E-01	3.352E+00
1.300E+02	1.014E+00	1.158E+00	4.282E+00	1.203E+00	6.212E-02	1.963E-02	0.000E+00	1.441E-01	3.315E+00
1.400E+02	9.996E-01	1.040E+00	4.353E+00	1.252E+00	6.331E-02	2.247E-02	0.000E+00	1.532E-01	3.271E+00
1.500E+02	9.925E-01	9.275E-01	4.447E+00	1.309E+00	6.511E-02	2.584E-02	0.000E+00	1.636E-01	3.251E+00

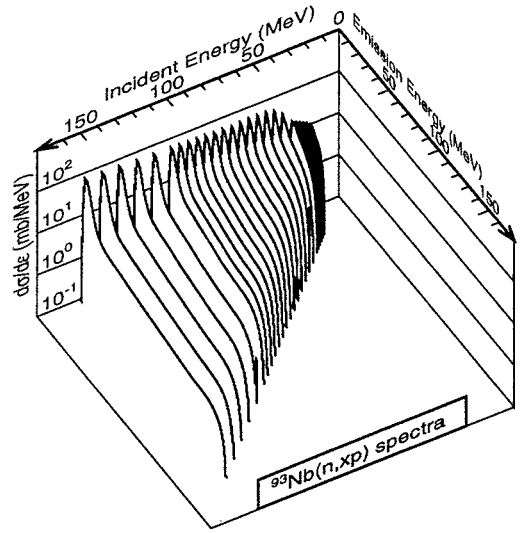
41093 = TARGET 1000Z+A (if A=0 then elemental)
1 = PROJECTILE 1000Z+A
Kerma coefficients in units of f.Gy.m^2:

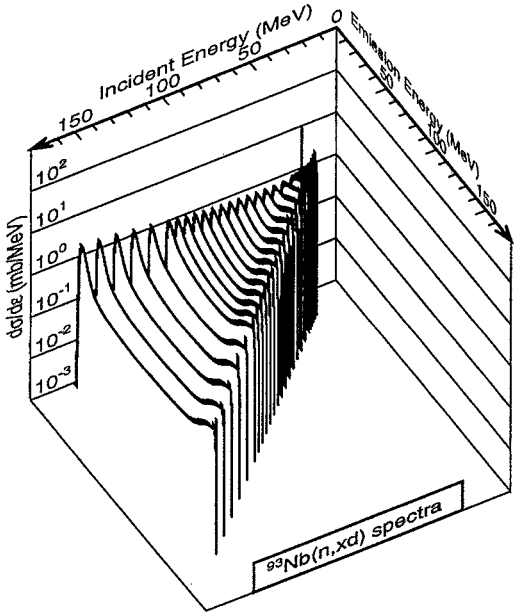
Energy	proton	deuteron	triton	helium3	alpha	non-rec	elas-rec	TOTAL
2.000E+01	1.725E-01	2.892E-02	2.534E-03	0.000E+00	3.192E-02	4.614E-02	8.936E-03	2.910E-01
2.200E+01	2.191E-01	3.770E-02	3.595E-03	0.000E+00	3.587E-02	4.940E-02	9.504E-03	3.551E-01
2.400E+01	2.692E-01	4.677E-02	4.698E-03	0.000E+00	3.936E-02	5.229E-02	1.007E-02	4.224E-01
2.600E+01	3.243E-01	5.624E-02	5.792E-03	0.000E+00	4.229E-02	5.482E-02	1.032E-02	4.937E-01
2.800E+01	3.869E-01	6.644E-02	6.859E-03	0.000E+00	4.487E-02	5.718E-02	1.017E-02	5.725E-01
3.000E+01	4.588E-01	7.711E-02	7.876E-03	0.000E+00	4.700E-02	5.941E-02	1.001E-02	6.602E-01
3.500E+01	6.592E-01	1.028E-01	1.022E-02	0.000E+00	5.094E-02	6.454E-02	9.425E-03	8.971E-01
4.000E+01	8.625E-01	1.281E-01	1.223E-02	0.000E+00	5.420E-02	6.934E-02	8.815E-03	1.135E+00
4.500E+01	1.056E+00	1.498E-01	1.393E-02	0.000E+00	5.762E-02	7.333E-02	8.347E-03	1.359E+00
5.000E+01	1.230E+00	1.707E-01	1.532E-02	0.000E+00	6.226E-02	7.658E-02	7.940E-03	1.563E+00
5.500E+01	1.391E+00	1.884E-01	1.657E-02	0.000E+00	6.917E-02	7.940E-02	7.572E-03	1.752E+00
6.000E+01	1.543E+00	2.008E-01	1.767E-02	0.000E+00	7.852E-02	8.163E-02	7.170E-03	1.929E+00
6.500E+01	1.690E+00	2.164E-01	1.863E-02	0.000E+00	8.967E-02	8.356E-02	6.901E-03	2.105E+00
7.000E+01	1.839E+00	2.347E-01	1.957E-02	0.000E+00	1.029E-01	8.581E-02	6.516E-03	2.289E+00
7.500E+01	1.981E+00	2.505E-01	2.037E-02	0.000E+00	1.151E-01	8.695E-02	6.195E-03	2.460E+00
8.000E+01	2.114E+00	2.643E-01	2.119E-02	0.000E+00	1.289E-01	8.816E-02	5.864E-03	2.622E+00
8.500E+01	2.240E+00	2.774E-01	2.204E-02	0.000E+00	1.431E-01	8.917E-02	5.588E-03	2.778E+00
9.000E+01	2.367E+00	2.904E-01	2.294E-02	0.000E+00	1.566E-01	9.005E-02	5.312E-03	2.932E+00
9.500E+01	2.490E+00	3.027E-01	2.399E-02	0.000E+00	1.704E-01	9.090E-02	4.984E-03	3.083E+00
1.000E+02	2.617E+00	3.153E-01	2.507E-02	0.000E+00	1.824E-01	9.152E-02	4.741E-03	3.236E+00
1.100E+02	2.873E+00	3.399E-01	2.755E-02	0.000E+00	2.051E-01	9.280E-02	4.226E-03	3.542E+00
1.200E+02	3.137E+00	3.621E-01	3.031E-02	0.000E+00	2.253E-01	9.376E-02	3.792E-03	3.853E+00
1.300E+02	3.416E+00	3.741E-01	3.357E-02	0.000E+00	2.459E-01	9.809E-02	3.417E-03	4.171E+00
1.400E+02	3.725E+00	3.941E-01	3.663E-02	0.000E+00	2.625E-01	1.033E-01	3.072E-03	4.525E+00
1.500E+02	4.054E+00	4.131E-01	4.023E-02	0.000E+00	2.813E-01	1.086E-01	2.745E-03	4.900E+00

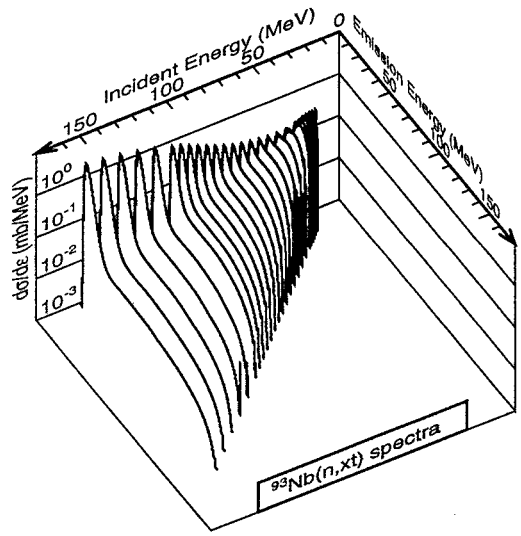

n + 93Nb nonelastic and production cross sections
Production Cross Section (mb)
10^4
10^3
10^2
10^1
n
γ
p
α
d
t
Nonelastic Cross Section (mb)
10^3
10^2
0
50
100
150
Incident Energy (MeV)

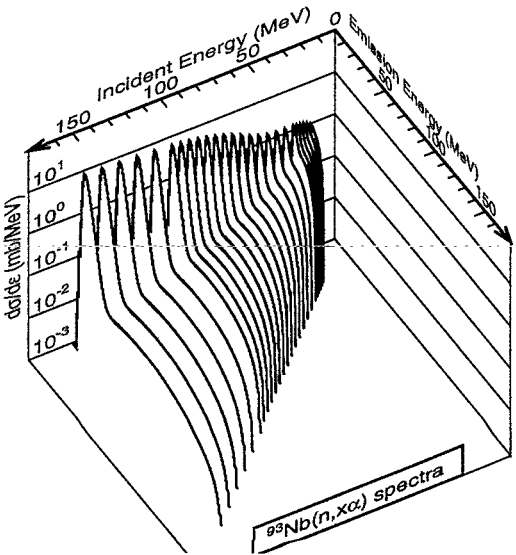
n + ^{93}Nb angle-integrated emission spectra

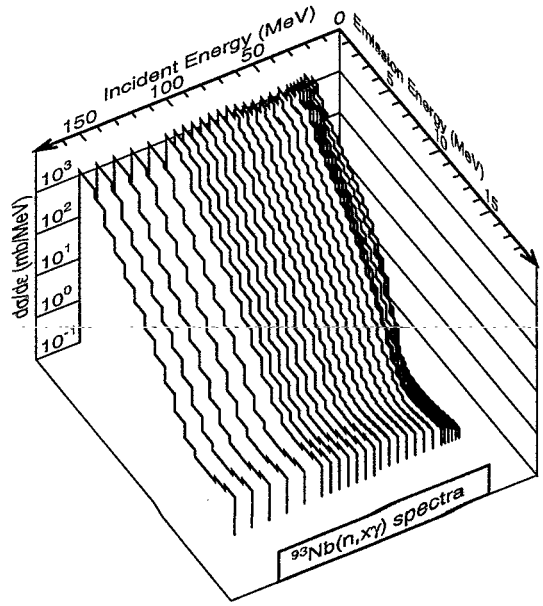




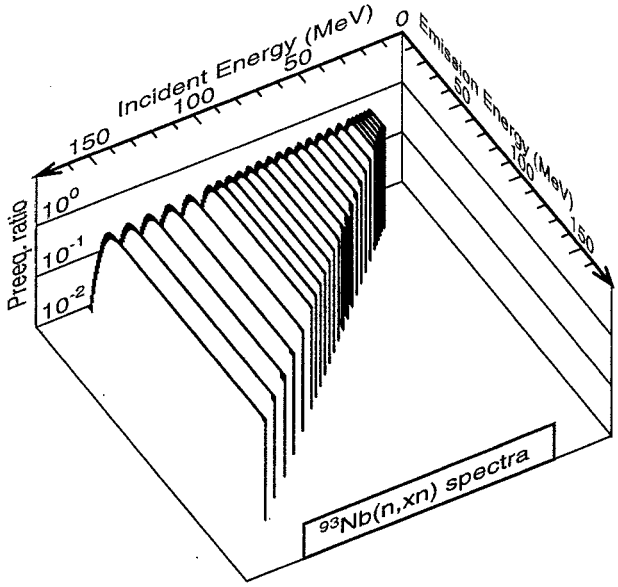


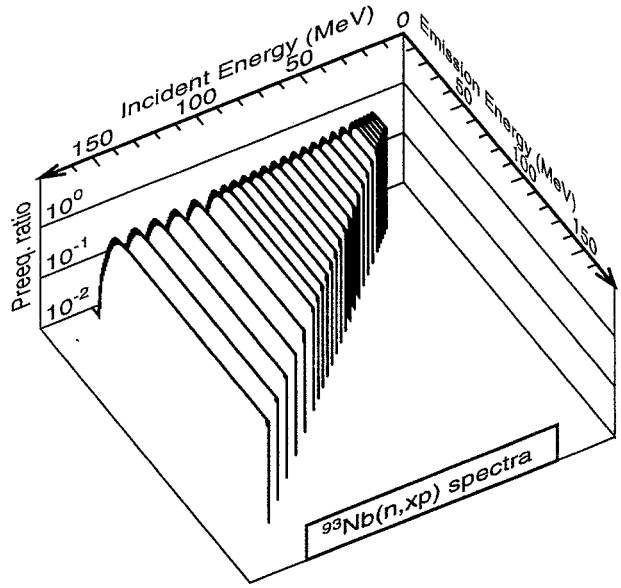


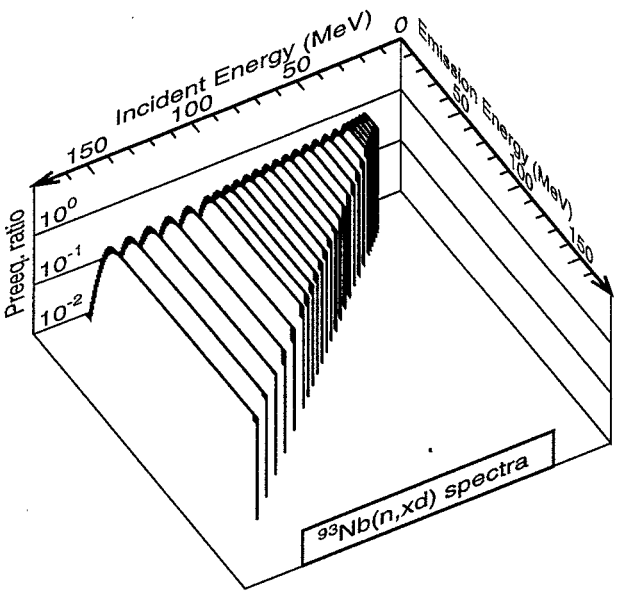


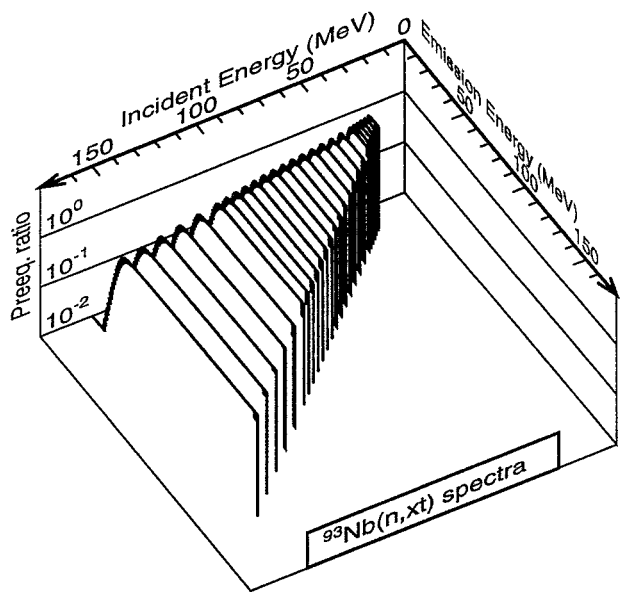


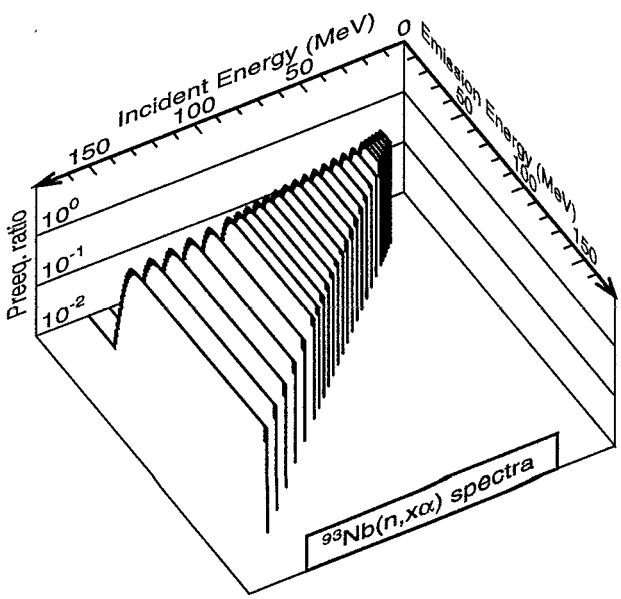
n + ^{93}Nb Kalbach preequilibrium ratios

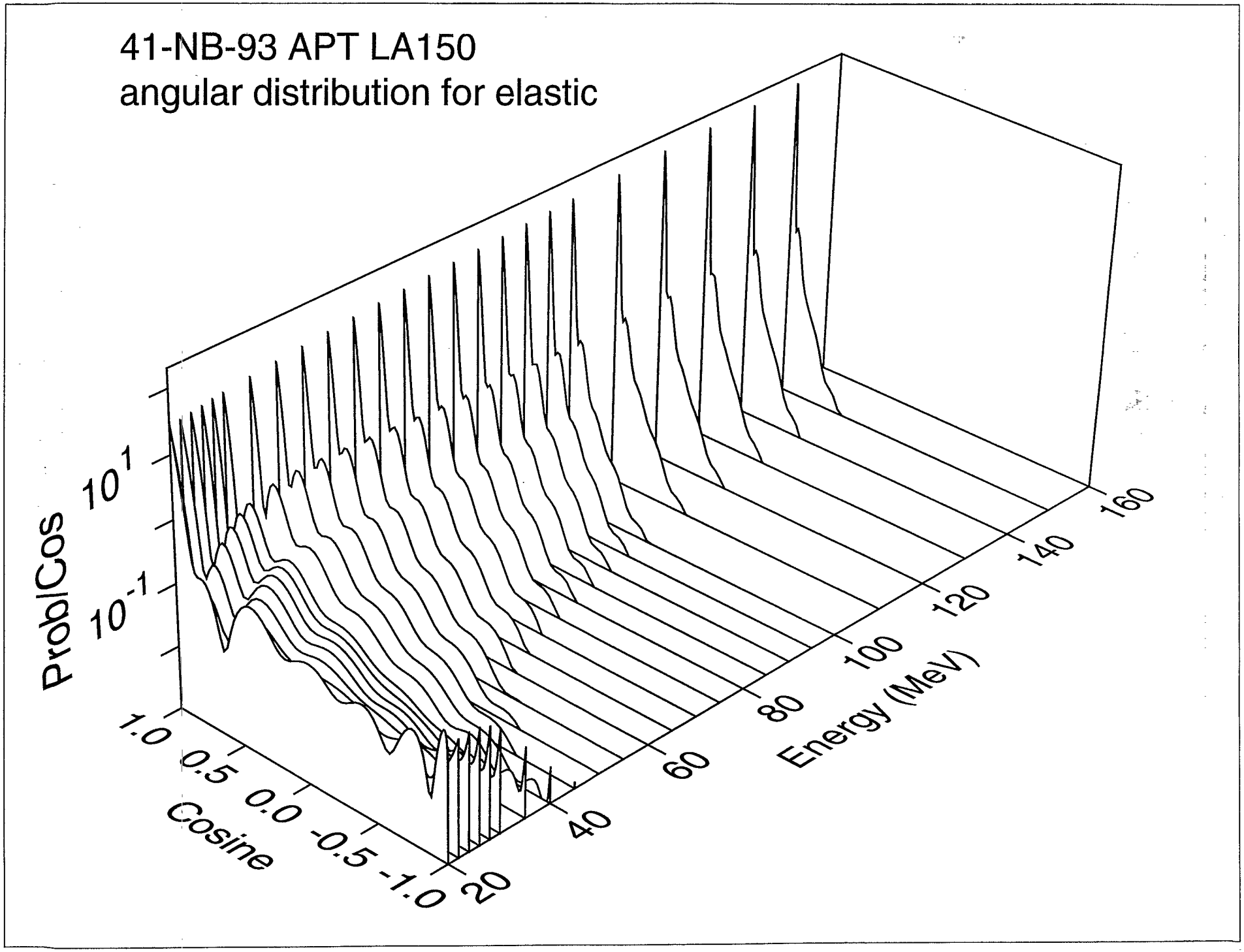











41-NB-93 APT LA150
angular distribution for elastic
Prob/Cos
10^1
10^{-1}
1.0
0.5
0.0
-0.5
-1.0
Cosine
20
40
60
80
100
120
140
160
Energy (MeV)