PICA95: AN INTRANUCLEAR-CASCADE CODE FOR 25-MeV TO 3.5-GeV PHOTON-INDUCED NUCLEAR REACTIONS*

C. Y. Fu, T. A. Gabriel and R. A. Lillie
Oak Ridge National Laboratory
P. O. Box 2008
Oak Ridge, Tennessee 37831-6364

Presented at the
Shielding Aspects of Accelerators, Targets, and Irradiation Facilities Meeting (SATIF-3)
Tohoku University
Sendai, Japan

May 12-13, 1997

*Managed by Lockheed Martin Energy Research Corporation for the U.S. Department of Energy under Contract No. DE-AC05-96OR22464.

DISCLAIMER

PICA95: An Intranuclear-Cascade Code for 25-MeV to 3.5-GeV Photon-Induced Nuclear Reactions

C. Y. Fu, T. A. Gabriel, and R. A. Lillie
Oak Ridge National Laboratory, Oak Ridge, TN 37831

Abstract

PICA95, an intranuclear-cascade code for calculating photon-induced nuclear reactions for incident photon energies up to 3.5 GeV, is an extension of the original PICA code package that works for incident photon energies up to 400 MeV. The original code includes the quasi-deuteron breakup and single-pion production channels. The extension to an incident photon energy of 3.5 GeV requires the addition of multiple-pion production channels capable of emitting up to five pions. Relativistic phase-space relations are used to conserve energy and momentum in multi-body breakups. Fermi motion of the struck nucleon is included in the phase-space calculations as well as secondary nuclear collisions of the produced particles. Calculated doubly differential cross sections for the productions of protons, neutrons, π^+, π^0, and π^- for incident photon energies of 500 MeV, 1 GeV, and 2 GeV are compared with predictions by other codes. Due to the sparsity of experimental data, more experiments are needed in order to refine the gamma nuclear collision model.

1. Introduction

The code package PICA[1,2], on which the present extension is based, contains three separate modules - PIC, MECCAN, and EVAP. The photon energy range in which the calculations are applicable is between approximately 25 and 400 MeV. All target nuclei with mass numbers greater than or equal to 4 are possible. The program PIC can accommodate incident mono-energetic photons as well as thin-target bremsstrahlung spectra, thin-target bremsstrahlung difference spectra and thick-target bremsstrahlung spectra. For the last type of spectra the user must furnish the photon spectral data. PIC writes a history tape containing data on the properties of the particles (protons, neutrons, π^+, π^0, or π^-) escaping from the nucleus. The data consists of the types of escaping particles and their energies and angles of emission. MECCAN utilizes the data of the PIC history tape to calculate cross sections such as the nonelastic cross section or the doubly differential cross section for each of the outgoing particles with energy-angle correlated distributions. EVAP then carries the nuclear reaction through the additional phase of evaporation. It calculates the energy spectra of particles (protons, neutrons, deuterons, tritons, ^{3}He, and alpha particles) "boiled off" from the excited nucleus after the cascade has stopped. Evaporation particle multiplicities and residual nuclei (radio-chemical) production cross sections can also be obtained.

PIC includes the quasi-deuteron breakup (photo-deuteron absorption) and single-pion production channels. At an incident photon energy of about 400 MeV, double-pion productions become possible. The present extension of PIC to an incident photon energy of 3.5 GeV requires the addition of multiple-pion production channels capable of emitting up to five pions. The total number of reaction channels increases from 5 in PICA to 41 in

PICA95. Cross sections for the major channels are taken from the recently evaluated data used in the EG code[3]. Cross sections for the reaction channels without experimental data are assumed to have the same shape as those with experimental data and with the same number of outgoing pions but can be scaled by an input factor (see details in Sections 2 and 3). Relativistic phase-space relations are used to conserve energy and momentum in multi-body breakups. Fermi motion of the target nucleon is included in the phase-space calculations as well as secondary nuclear collisions of the produced particles.

The upper incident photon energy in PICA95 is limited by the secondary particle cascade part of PIC. Intranuclear cascades of the secondary particles (protons, neutrons, π^+, π^0, or π^-), produced by the primary photon interaction with nucleons, are based on the MECC code of Bertini[4]. In MECC, the upper energy limit for pions is 2.5 GeV and that for nucleons is 3.5 GeV. In PICA95, secondary pions of energies greater than 2.5 GeV is set to 2.5 GeV before MECC subroutines are called to continue the intranuclear cascades. This procedure causes a truncation in the pion production spectra for incident photon energies between 2.7 GeV and 3.5 GeV but the loss in the total energy of pion production for an incident photon energy of 3.5 GeV is less than 2%.

The new code package PICA95 changes only PIC. MECCAN and EVAP still work the same way as described in Ref. 2. Calculated doubly differential cross sections for the productions of protons, neutrons, π^+, π^0, and π^- for incident photon energies of 500 MeV and 1 GeV are compared with predictions using CEM95[5,6] and by Degtyarenko[7] using DINREG[8,9]. For the incident photon energy of 2 GeV, comparisons are made only with DINREG. CEM95 is an intranuclear cascade code similar to PICA95 but is limited to incident photon energies below 1 GeV, above which the triple-pion contributions, not included in CEM95, become significant. Differences in the predicted particle production spectra between PICA95 and CEM95 may be due to differences in the input cross sections, nucleon densities, nuclear level densities, and pion potentials. DINREG is not an intranuclear cascade code but is based on entirely different concepts such as a thermodynamic quark source in the excited nucleus, the rules of high-energy hadron production, and some empirical parameters derived from electron-induced reactions. DINREG has been used up to 10 GeV but a detailed documentation of DINREG is not yet available.

2. Multi-Pion Channels

The reaction channels included in PICA95 are listed in Table 1. The first five channels are used in PICA while all 41 channels are included in PICA95. Cross sections for the channels used in PICA95 and the method used for conserving energy and momemtum are described in this section.

The cross section for reaction number 1, the γ(n,p) channel, is the same as the cross section adopted for PICA up to 660 MeV. For PICA95, this cross section is extended above 660 MeV by assuming it to decrease with increasing photon energies in proportion with the fourth power of the photon energy. The angular distributions of the produced protons are tabulated in PICA for incident photon energies up to 600 MeV. For incident photon energies greater than 600 MeV, this angular distribution is assumed in PICA95 to be isotropic in the center of mass of the excited pseudo deuteron.

The cross sections for reaction numbers 2, 4, 6, 12, 20, and 30 were taken from the EG code[3] that considered the most recent experimental data for these cross sections. These cross sections and that of reaction 1 are shown in Fig. 1. The cross sections of reactions 3 and 5 are set to be the same as 2 and 4, respectively, assuming charge symmetry. All double-pion cross sections are assumed to have the same cross section shape as channel number 6 but may be scaled by an input factor. The same approach is used for scaling all other triple-pion cross sections to channel number 12, four-pion cross sections to channel number 20, and five-pion cross sections to channel number 30. The values of the scaling factors used in the present calculations are given in Section 3.

In Table 1, the cross sections tabulated in the EG code are marked. These are reaction numbers 2-6, 12, 13, 20, 30, 33. However, not all of these cross sections are tabulated in PICA95. In PICA95, the cross sections of reactions 3 and 5 have been set to 2 and 4, respectively, as discribed above assuming charge symmetry. The cross section of reaction number 13 has been set equal to that of 12 because these two cross sections are rather close. For the same reason, the cross section of reaction 33 has been set equal to that of 30. Therefore, only cross sections for reaction numbers 1, 2, 4, 6, 12, 20, and 30 are tabulated in PICA95 as shown in Fig. 1. As discussed above, scale factors can be used to alter these cross sections. In fact, most of the cross sections are weakly known and need to be refined.

The decision to use scale factors for unknown cross sections is based on an observation of the assumptions used in the CEM95 and EG codes. CEM95 includes channel numbers 8 and 10, the double-π^0 productions, while EG ignores them. These two extreme assumptions tend to make a factor of two difference in π^0 production spectra near an incident photon energy of 1.25 GeV where the double-pion production cross section (see Fig. 1) is the largest. It is therefore better to keep the multi-π^0 channels open until new experimental data are available to help make a good decision on the scaling factors. It is easier to set a cross section to a different value than to add a new reaction channel into the code.

In PICA, only two-particle relativistic kinematics with Fermi motion of the struck nucleon are needed. But multi-particle relativistic kinematics with Fermi motion are also required in PICA95. The latter requirement is met by combining standard relativistic phase-space relations with the two-body kinematics with the Fermi motion already in PICA.

Many other reaction channels, containing outgoing particles like deltas, rhos, etas, omegas, etc., are open for an incident photon energy of 3.5 GeV. In particular, delta and rho channels are open below 500 MeV. These channels are not included in PICA95. Even though these missing reaction channels have small cross sections[3], most of them, including the delta and rho channels, produce protons, neutrons, or pions. So their absence tends to make the present PICA95 results underpredict by up to 30%.

3. Comparisons with Other Calculations

The PICA95 results presented in this section were obtained using scale factors for the cross sections that are unity except for multiple-π^0 cross sections that have scale factors inversely proportional to the number of π^0's produced. As examples, the scale factors for reaction numbers 8 and 10, the double-π^0 channels, are 1/2 and the scale factors for reaction numbers 32 and 38, the five-π^0 channels, are 1/5. These scale factors represent an intermediate choice between the assumptions made in the CEM95 and EG codes.

Calculated double differential cross sections for Cu for the production of protons, neutrons, π^+, and π^0 for incident photon energies of 500 MeV and 1 GeV are compared with predictions using CEM95 by authors of this report and using DINREG by Degtyarenko in Figs. 2-5. For the incident photon energy of 2 GeV, the comparisons shown in Figs. 6 and 7 are only with DINREG. The energy spectra for π^- are omitted in this report because they are very similar to those for π^+. Each figure compares the energy spectra in two angular groups - the forward angles (0 to 90 degrees laboratory) and the backward angles (90 to 180 degrees laboratory). The spectral comparisons are for outgoing particles having energies greater than 25 MeV. For energies below 25 MeV the spectral comparisons are listed in tables as discussed below. All symbols in Figs. 2-7 represent histograms that are shown only for one set of spectra. The spectra for the backward angles have been scaled in the figures by a factor of 0.1 for clarity.

The total reaction cross sections and particle multiplicities are given in Tables 2 and 3. The product of a particle multiplicity and the total reaction cross section gives the energy-integrated cross section for the production of that particle. Table 2 corresponds to the forward-angle data above 25 MeV shown in the figures. Table 3 is for total multiplicities including the backward angles and all energies. PICA95 yields the smallest reaction cross sections and the largest multiplicities. For protons and neutrons, the multiplicities from DINREG are between PICA95 and CEM95. For pions, PICA95 is closer to CEM95 than to DINREG.

The large multiplicities predicted by PICA95 could be partly due to the lack of a pre-equilibrium reaction model that would bridge the gap between the existing intranuclear cascade and evaporation models. In addition, the EVAP code does not include the subtraction of recoil energy from the excitation energy. Inclusion of both in PICA95 would lead to smaller multiplicities.

Figures 2-7 show that the spectral shapes for protons and neutrons in the three calculations are similar, but those for pions are only similar between PICA95 and CEM95. The minima in the pion spectra near 150 MeV, seen in CEM95 and PICA95, are not in DINREG. These minima can be well-explained by the large pion resonance[4] at 150 MeV that scatters or absorbs pions produced near the resonance. The 2-GeV comparisons between CEM95 and DINREG, the proton and neutron spectra are in good agreement in magnitude and in shape, and the pion spectra are in good agreement in shape except at 150 MeV.

4. Conclusions

Proton, neutron, π^+, π^0, and π^- spectra produced by high-energy photons on Cu calculated by PICA95 are compared with results predicted by CEM95 at 500 MeV and 1 GeV, and with results predicted by DINREG at 500 MeV, 1 GeV, and 2 GeV. Predicted reaction cross sections by the three codes agree within 50%, but multiplicities differ by a factor of 2 for nucleons and by a factor of 4 for pions. Shapes of the nucleon spectra are in good agreement for all cases shown, but shapes of the pion spectra by DINREG do not show the large dips near 150 MeV seen in the PICA95 and CEM95 results, particularly for the 500-MeV comparions.

The comparisons shown in this report represent the status of the predictive capabilities of photonuclear codes available for photon energies in the low-GeV range. Improvements in theory and/or adjustments in input cross sections and parameters may be required when new experimental data become available. Until then, codes compared in this report are being applied to aid in the design of high-energy detectors, in the interpretation of data acquired in such detectors, and in the assessment of radiation doses in and around proposed accelerators[7].

An addition of pre-equilibrium reaction model in PICA95 to link the existing intranuclear cascade and evaporation models is in progress.

ACKNOWLEDGMENTS

The authors acknowledge help from Stephan Mashnik of Dubna, Russia for making CEM95 operational at Oak Ridge National Laboratoty, P. Covisiero of Genova, Italy for sending the EG code, and Pavel Degtyarenko of CEBAF for sending his calculated results for Cu. This work was sponsored by Office of Energy Research, Division of Nuclear Research, U. S. Department of Energy, under contract DE-AC05-84OR21400 with Lockheed Martin Energy Systems, Inc.

REFERENCES

1. T. A. Gabriel and R. G. Alsmiller, Jr., "Photonuclear Disintegration at High Energies (350 MeV)", Phys. Rev 181, 1035 (1969) and ORNL-TM-2481 (February 1969).
2. T. A. Gabriel, M. P. Guthrie, and O. W. Hermann, "Instructions for the Operation of the Program Package PICA, An Instranuclear-Cascade Calculation for High-Energy (20 to 400 MeV) Photon-Induced Nuclear Reactions," ORNL-4687 (September 1971).
3. P. Corvisiero et al., Nuc. Inst. Med. A346, 433-440 (1994).
4. Hugo W. Bertini, "Intranuclear Cascade Calculation of the Secondary Nucleon Spectra from Nucleon-Induced Interactions in the Energy Rangy Range 340 to 2900 MeV and Comparisons with Experiment," Phys. Rev. 188, 1711-1730 (1969).
5. T. Gabriel, G. Maino, S. G. Mashnik, "Analysis of Intermediate Energy Photonuclear Reactions," XII International Seminar on High Energy Physics Problems - Relativistic Nuclear Physics and Quantum Chromodynamics, E2-94-424, Dubna, Russia, 12-17 September, 1994.
6. Stephan G. Mashnik, "User Manual for the code CEM95," Bogoliubov Laboratory of Theoretical Physics, Joint Institute for Nuclear Research, Dubra, Russia, 1995.
7. P. V. Degtyarenko and G. Stapleton, "Radiation for High Energy Electron Accelerators - Past and Future", a presentation at the second workshop on Simulation Accelerator Radiation Environment (SARE2), 9-11 October 1995, CERN, Geneva, Switzerland.
8. M. V. Kossov, "Monte Carlo Generator for nuclear fragmentation induced by pion capture," MC93 International Conference on Monte Carlo Simulation in High Energy and Nuclear Physics, Tallahassee, Florida, USA, 22-26 February 1993, p.190.
9. P. V. Degtyarenko et al., Phys. Rev. C50, 541 (1994).

Table 1. Reaction channels used in PICA95

Reaction number	Struck particle	Exit particles
1 *	(n.p)	n p
2 *	p	n pi+
3 *	n	p pi-
4 *	p	p pi0
5 *	n	n pi0
6 *	p	p pi+ pi-
7	p	n pi+ pi0
8	p	p pi0 pi0
9	n	n pi+ pi-
10	n	p pi- pi0
11	n	n pi0 pi0
12 *	p	p pi+ pi- pi0
13 *	p	n pi+ pi+ pi-
14	p	n pi+ pi0 pi0
15	p	p pi0 pi0 pi0
16	n	n pi+ pi- pi0
17	n	p pi+ pi- pi-
18	n	p pi- pi0 pi0
19	n	n pi0 pi0 pi0
20 *	p	p pi+ pi+ pi- pi-
21	p	p pi+ pi- pi0 pi0
22	p	p pi0 pi0 pi0 pi0
23	p	n pi+ pi+ pi- pi0
24	p	n pi+ pi0 pi0 pi0
25	n	n pi+ pi+ pi- pi-
26	n	n pi+ pi- pi0 pi0
27	n	n pi0 pi0 pi0 pi0
28	n	p pi+ pi- pi- pi0
29	n	p pi- pi0 pi0 pi0
30 *	p	p pi+ pi+ pi- pi- pi0
31	p	p pi+ pi- pi0 pi0 pi0
32	p	p pi0 pi0 pi0 pi0 pi0
33 *	p	n pi+ pi+ pi+ pi- pi-
34	p	n pi+ pi+ pi- pi0 pi0
35	p	n pi+ pi0 pi0 pi0 pi0
36	n	n pi+ pi+ pi- pi- pi0
37	n	n pi+ pi- pi0 pi0 pi0
38	n	n pi0 pi0 pi0 pi0 pi0
39	n	p pi+ pi+ pi- pi- pi-
40	n	p pi+ pi- pi- pi0 pi0
41	n	p pi- pi0 pi0 pi0 pi0

* cross section known to some extent (refs. 1,3)

Table 2. Comparisons of total reaction cross-sections and multiplicities (>25 MeV, forward angles) for Cu

Energy (MeV)		Total XS (mb)	multiplicity (>25 MeV, <90 deg)				
			p	n	pi+	pi0	pi-
500	PICA95	10.18	1.35	1.53	.181	.220	.219
	CEM95	11.21	.790	.960	.109	.125	.127
	DINREG	15.14	.823	1.30	.050	.100	.042
1000	PICA95	8.33	1.97	2.22	.436	.496	.480
	CEM95	9.18	1.07	1.30	.191	.262	.238
	DINREG	9.95	1.51	2.09	.093	.142	.085
2000	PICA95	5.73	3.12	3.59	.900	1.01	.960
	DINREG	7.70	2.51	3.25	.253	.340	.254

Table 3. Comparisons of total reaction cross-sections and multiplicities (all energy, all angle) for Cu

Energy (MeV)		Total XS (mb)	multiplicity (all energy angle))				
			p	n	pi+	pi0	pi-
500	PICA95	10.18	4.88	7.16	.309	.385	.376
	CEM95	11.21	2.33	4.20	.175	.201	.209
	DINREG	15.14	2.45	4.87	.074	.153	.064
1000	PICA95	8.33	6.71	9.18	.683	.784	.752
	CEM95	9.18	2.88	4.61	.283	.392	.339
	DINREG	9.95	4.13	7.00	.120	.194	.119
2000	PICA95	5.73	10.47	13.73	1.310	1.516	1.427
	DINREG	7.70	6.85	10.38	.305	.425	.302

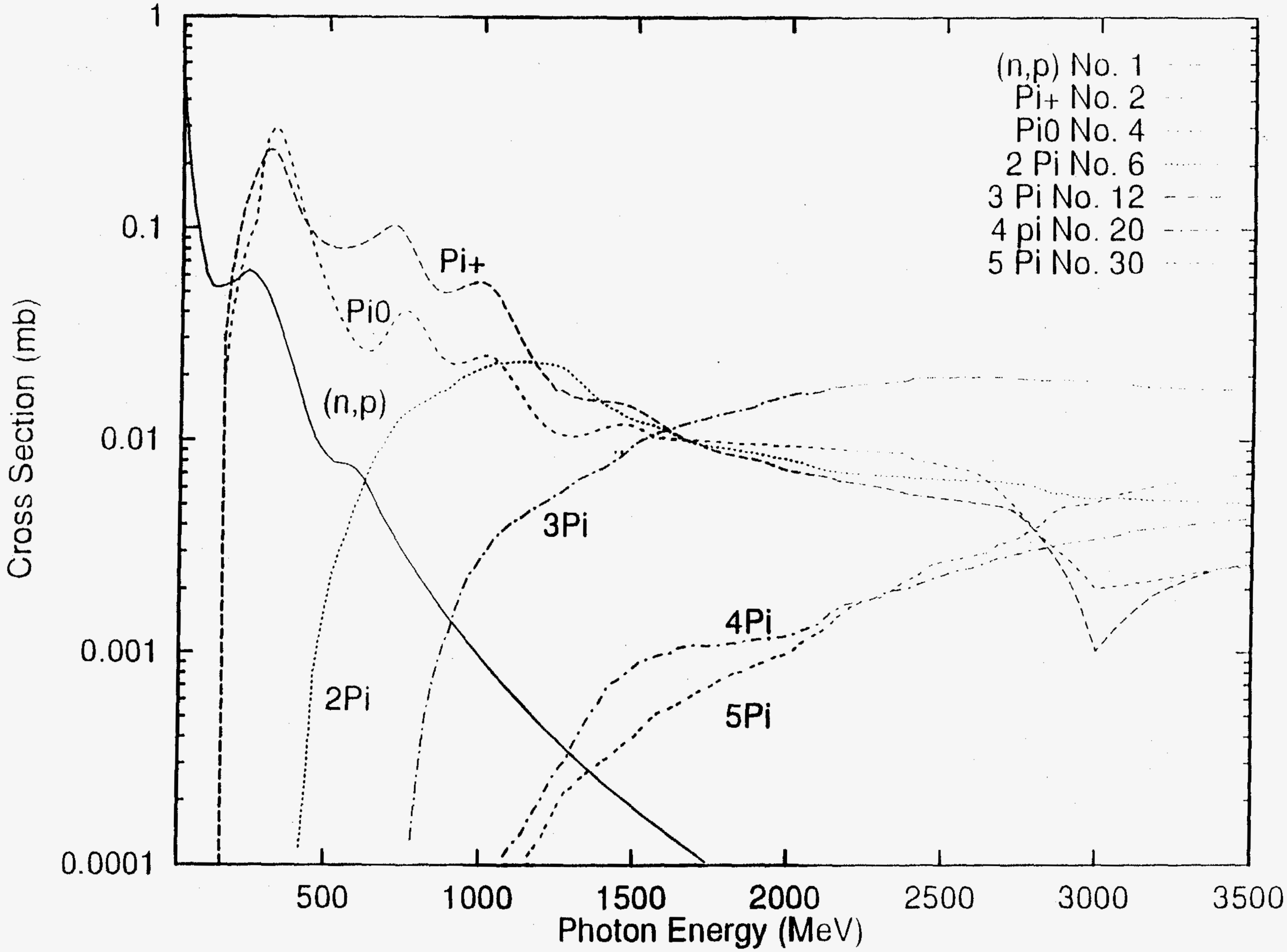

Fig. 1 Cross sections of photon-induced reactions tabulated in PICA95. The reaction number shown corresponds to that listed in Table 1.

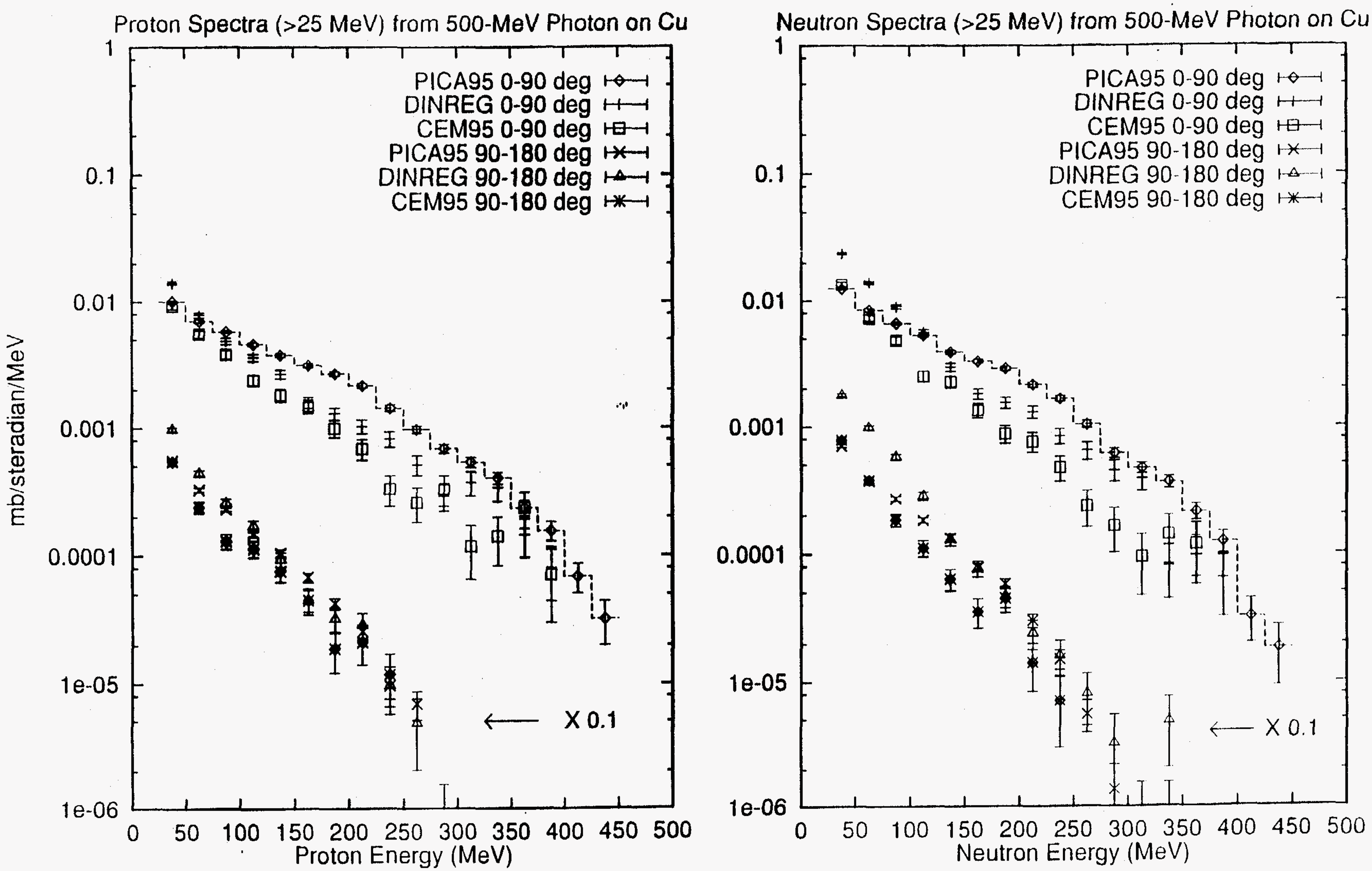

Fig. 2 Proton and neutron spectra from 500-MeV photon on Cu.

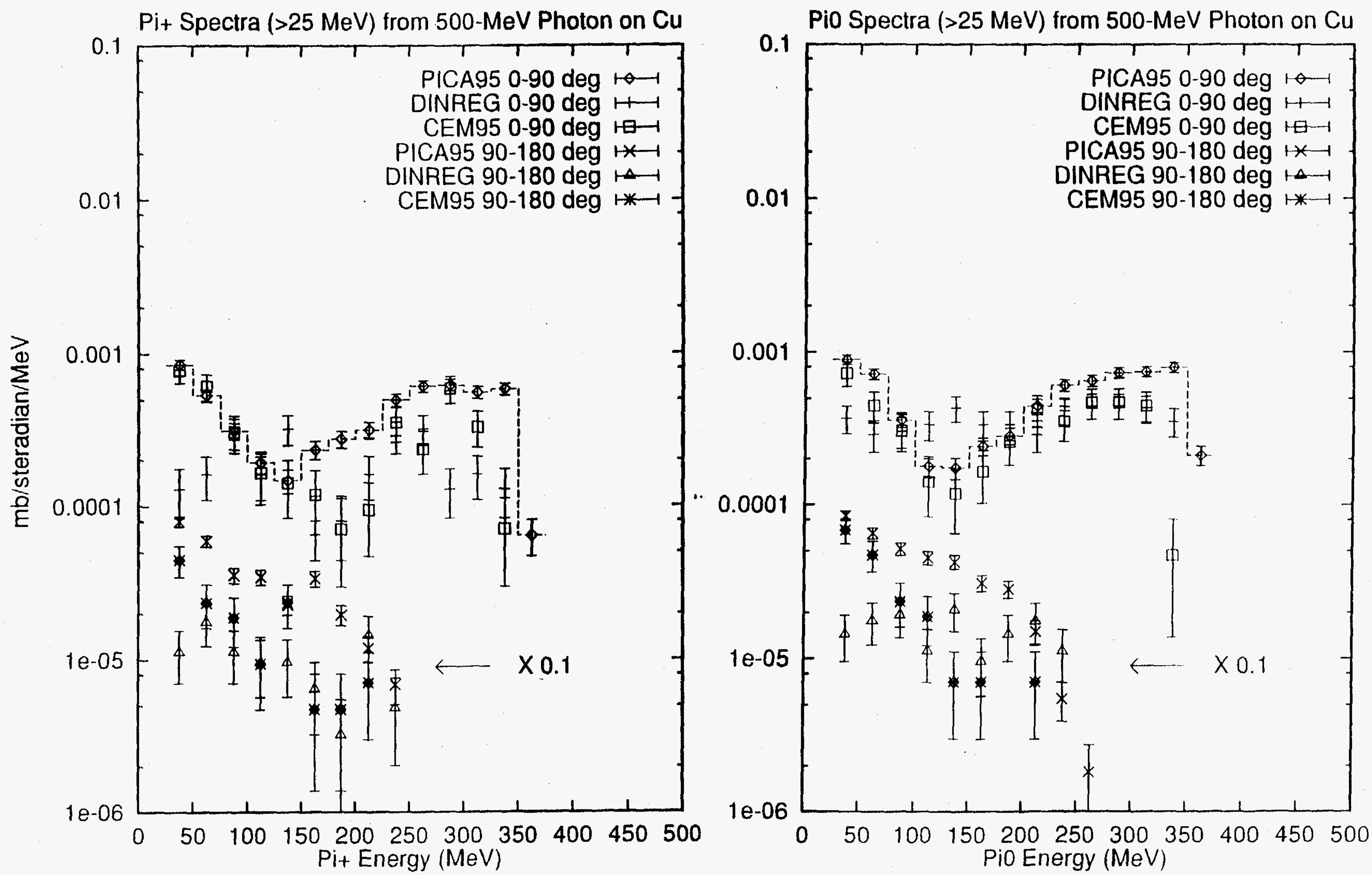

Fig. 3 π^+ and π^0 spectra from 500-MeV photon on Cu.

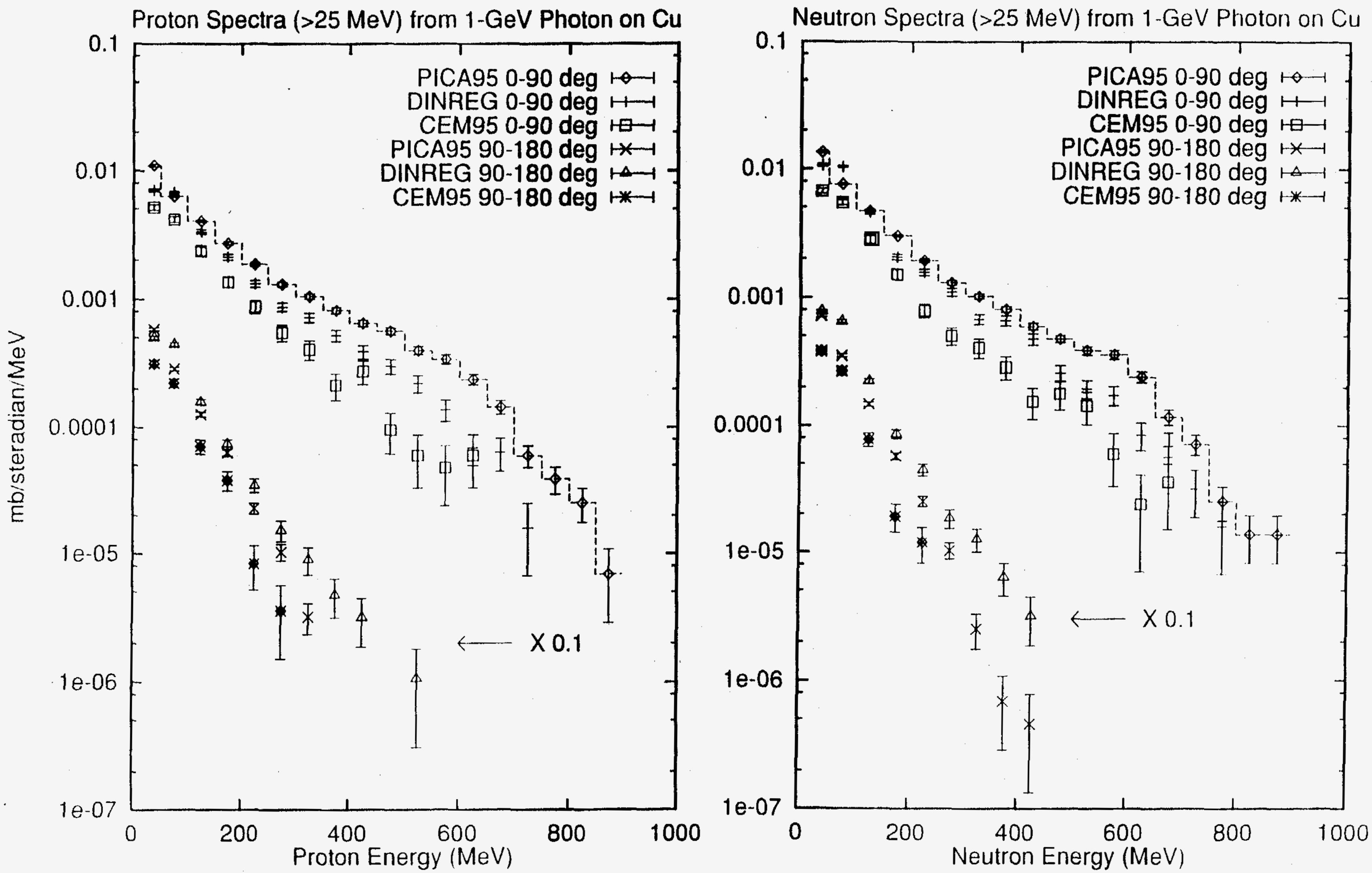

Fig. 4 Proton and neutron spectra from 1-GeV photon on Cu.

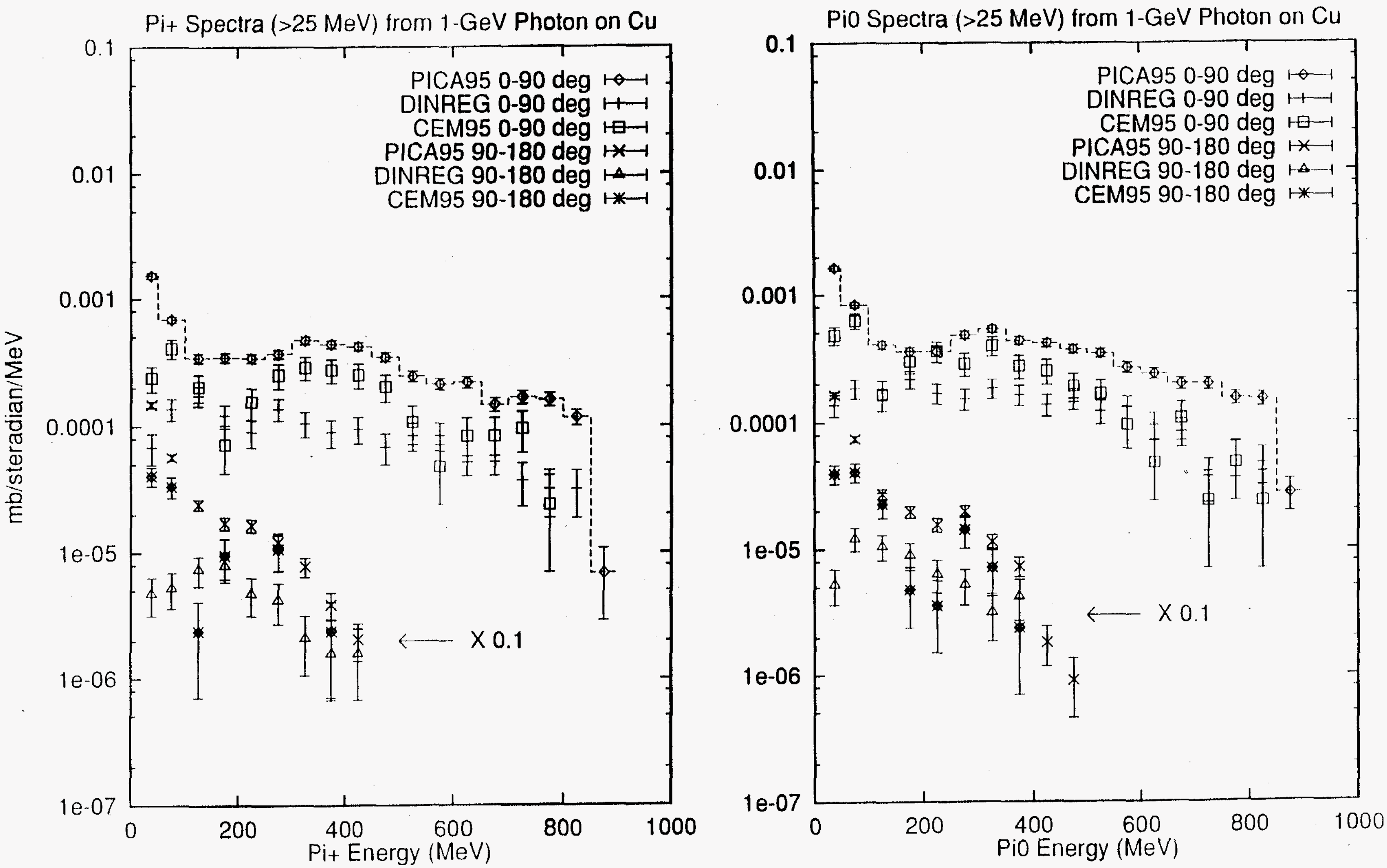

Fig. 5 π^+ and π^0 spectra from 1-GeV photon on Cu.

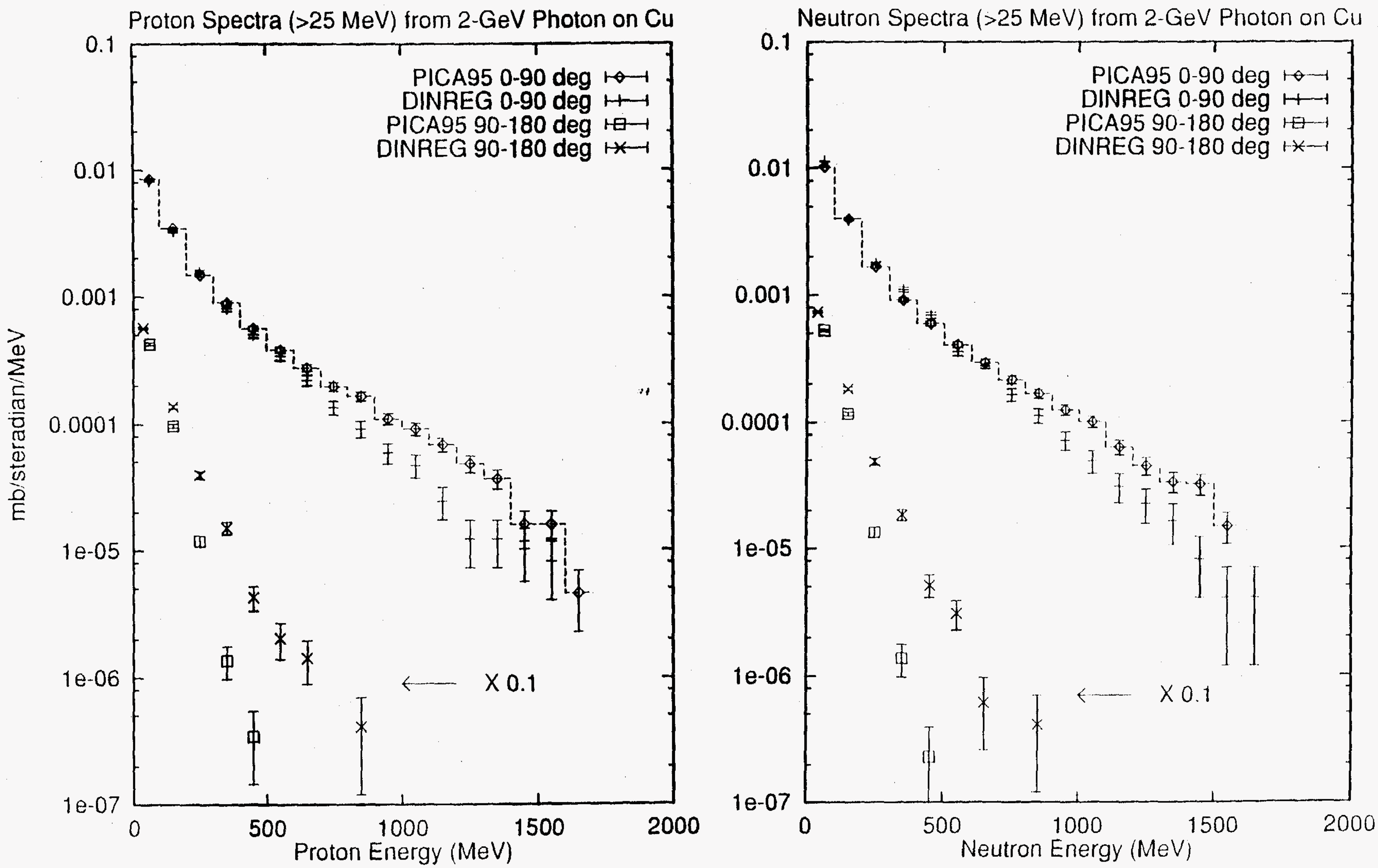

Fig. 6 Proton and neutron spectra from 2-GeV photon on Cu.

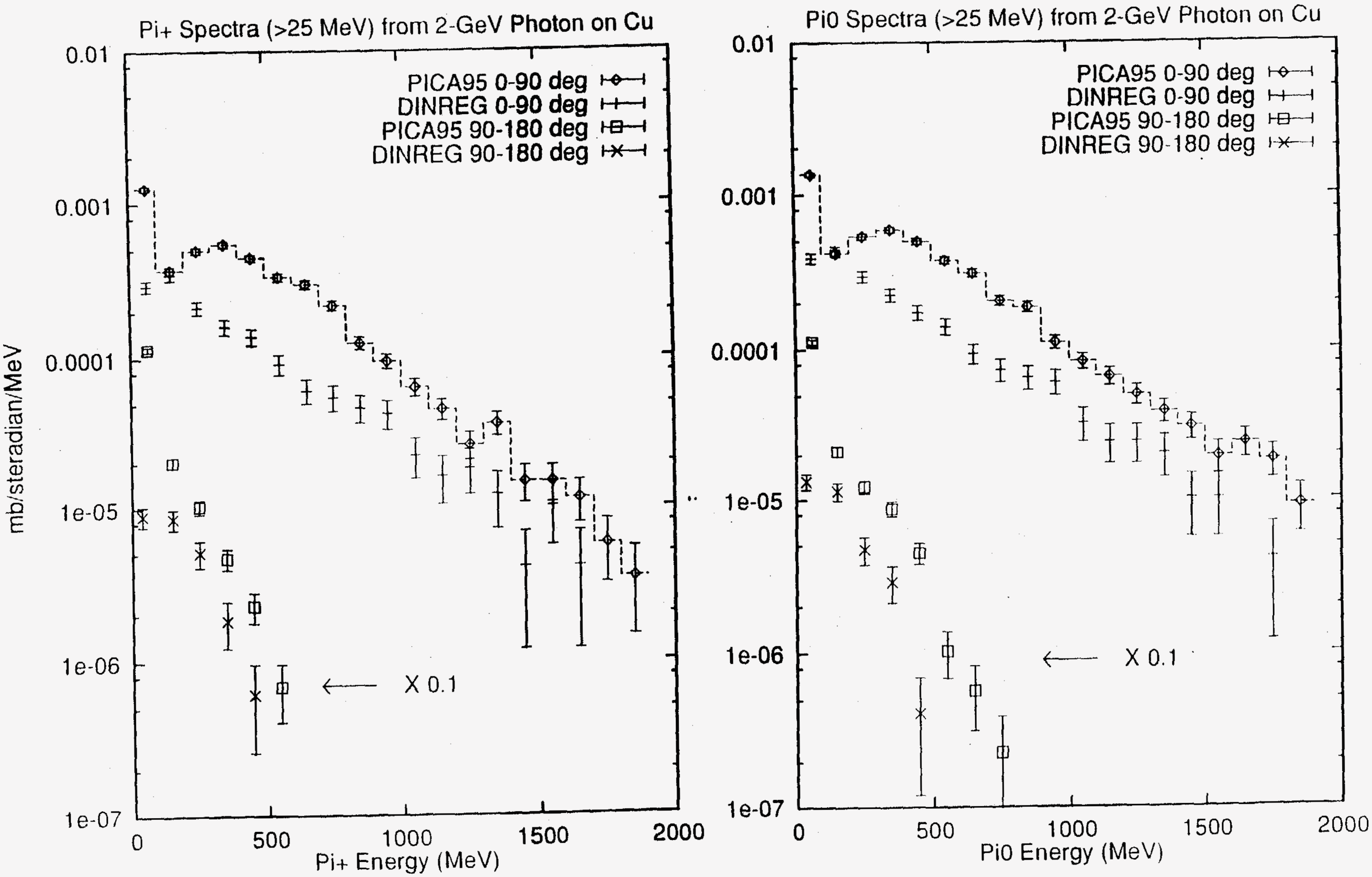

Fig. 7 π^+ and π^0 spectra from 2-GeV photon on Cu.