Nuclear Models in FLUKA for Interactions in the Intermediate Energy Range

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Abstract

The FLUKA Monte Carlo code is able to simulate the interaction and transport of hadronic and electromagnetic showers over a large energy range, from a few tens of TeV down to thermal energies for neutrons. The code contains several nuclear interaction models to cover the whole energy range of interest. The performances in the intermediate hadron energy range have been extensively improved in the last years through the implementation of feasible and modern physical models. Examples of the results are presented in this paper.

1. Introduction

The FLUKA Monte Carlo code in its most recent version [1, 2, 3, 4, 5] is extensively used for simulating hadron and electromagnetic showers. A review of its present fields of applications can be found in [4, 5].

FLUKA is not the only code capable of simulating a whole high-energy hadronic cascade from TeV to thermal energies. Several other systems, CALOR, HERMES, LAHET [6, 7, 8] are available, but most of them differ from FLUKA by being essentially built as assemblies of different specialized codes, one for each of the main radiation components (hadronic cascade and muons, electromagnetic shower, low energy neutrons), which communicate with each other off-line via an exchange of files. In such systems, each component code keeps in general its own characteristics and structure. Instead FLUKA handles the complete cascade in a single run, and the treatment of the various components has been integrated as far as possible. There are obvious advantages in this approach. Furthermore the parts of FLUKA dealing with the various cascade components have been recently developed and incorporate very advanced physics, instead to resort to glorious but no longer up-to-date models, like the original EGS4 [9] or the Bertini INC model [10]. There is still another code, the well known GEANT package developed at CERN [11], which can be compared with FLUKA, at least to the extent that both are able to simulate in detail and in a single run the hadronic as well as the electromagnetic cascade. However, the GEANT description of the hadronic interactions is done through interfaces to existing hadronic codes, which have a life of their own and are not fully incorporated into its structure (The last version, 3.21, has as optional hadronic event generator that of FLUKA, including a simplified version of the preequilibrium-cascade model, which was completely missing in the previous version 3.15).

For many years FLUKA has been known as one of the main tools for designing shielding of proton accelerators in the multi-GeV energy range. Its high energy hadron event generator [2] has been adopted by the majority of the existing high-energy transport codes [12, 7, 8], including those used for particle physics simulations [6, 11]. However, since 1991 FLUKA contains also a sophisticated model to allow meaningful simulations of interactions in the intermediate energy range. This model, called PEANUT [5, 13, 14], uses an integrated IntraNuclearCascade (INC) plus statistical (GDH like) description: details can be found in [5, 13, 14]. For the present paper it suffices to say that it has been designed in such a way to overcome most of the limitations of classical INC algorithms. In fact, it is well known that standard INC codes, like the one originally developed by H. Bertini [10], have severe limitations for incident energies below few hundreds of MeV [15, 16, 17], that in some way limit their applicability. Furthermore most INC codes use average binding energies which are a reasonable approximation for very high energies but results in poor comparisons with experimental data because of the incorrect calculation of reaction Q's as soon as the incident energy is below a few tens of MeV.

Following the publication of an international intercomparison organized by the Nuclear Energy Agency [18], it was felt desirable to clarify what actually are the capabilities of the FLUKA code in this field. As a consequence a contribution as similar as possible to the one originally requested for the intercomparison was presented at this workshop and is illustrated in the following. Other examples of code performances with respect to both thin and thick target problems can be found in [5, 14, 19, 20].

2. Results

The complete set of double differential cross sections for ^{90}Zr and ^{208}Pb for which a recent international intercomparison has been organized [18] has been simulated with PEANUT [5, 13, 14] as implemented in FLUKA. The graphs showing the obtained results as well as the experimental data (see the ref. in [18]) are presented in the following together with the questionnaire requested for the intercomparison.

In all graphs the Monte Carlo results are presented as histograms with shaded areas corresponding to 1 σ error bars. The experimental data are plotted as symbols connected with a line to guide the eyes. Different experimental data sets, when available, have been plotted on the same drawing with different symbols. For lead at 800 MeV besides the experimental data coming from the Los Alamos group, there are two experimental sets corresponding to two different efficiency calibrations used by the Hamburg group. For all other targets/energies th Hamburg group data was available only for one of the two calibrations. Errors bars when available are plotted on the experimental points. It should be stressed that all graphs have been obtained with a standard set of parameters for PEANUT with no effort to match the data as a function of target/energy. The adopted reaction cross sections were always the ones coming from systematics.

FLUKA
Code information Questionnaire

I. General Questions

1. **Name of the code**
   FLUKA
2. **Name of the participant**
   Alfredo Ferrari
3. **Responsible author of the code**
   A. Fassò, CERN
   A. Ferrari, P.R. Sala, INFN, Sezione di Milano
   J. Ranft, INFN, Laboratori Nazionali di Frascati
4. **Reference of the code**
   See references [1, 2, 4, 5, 13, 14] at the end of the Questionnaire.
5. **Is a manual available ?**
   Not yet, it is in preparation. A draft is available.
6. **What nuclear reaction models are contained?**
   FLUKA uses different models depending on the energy range:
   Primary interactions between 1 GeV and 5 GeV/c are described via resonance production and decay, and above 5 GeV/c by multichain fragmentation in the frame of the Dual Parton Model (DPM). Both models are improved and updated versions of those described in ref. [21, 22] The possibility of multiple primary collisions is accounted for in a simplified Glauber cascade framework, and diffractive events are also modelled. Primary interactions are followed by a cascade and an evaporation step. The INC description makes use of parametrized multiplicities and energy-angle distributions properly correlated with primary collisions and among each other (see [23]).
   Below 1 GeV (3 GeV if Kaon production can be neglected) we use the PEANUT code, that includes:
   - Intranuclear Cascade
   - Precompound decay (geometry dependent hybrid model)
   - Evaporation (statistical)
   - Fission following the model of Atchison[24].
   - Pion production through resonance formation.
   - Pion scattering and absorption

   As an option, the program DTUNUC[25] can be used from 5 TeV down to a few hundreds of MeV, both for hadron-nucleus and nucleus-nucleus collisions. It applies the Dual Parton Model in a Glauber multiple scattering treatment, and includes the cascading (suppressed by the formation time mechanism) of secondaries within the target as well as in the projectile.
7. **Range of targets allowed**
   A=1, A≥4
8. **Range of projectiles allowed**
   Particles normally used as projectiles are: $p, n, e^+, e^-, \gamma, \pi, \mu, K, \bar{p}, \bar{n}$
   All other stable (with respect to strong decay) hadrons (including all hyperons and antihyperons) can be transported by the code and their interactions can be managed down to 2.5 GeV.
9. **Incident energy regime permitted**
   0 - 20 TeV

II. Specific questions

Answers are intended to be restricted to the PEANUT package and to the case of proton or neutron induced reactions.

1. **How are reaction cross-sections generated in the entrance channel?**
   Reaction Cross sections are taken from systematics. The program can calculate them : calculated results agree with systematics within 10% except for low energies, where results are very sensitive to details of the adopted nuclear potential.
2. **What nuclear density distribution is used, and how does it enter the calculation?**
   Density distribution has a symmetrized Woods-Saxon shape, subdivided in 16 zones. Enters in the calculations of potentials and mean free paths. Precompound part is density dependent (GDH).
3. **Is the Fermi energy calculated in a local density approximation?**
   Yes.
4. **What nuclear radius parametrization is used?**
   The nuclear radius derives from normalization of the nuclear density distribution: central density is $\rho_o = 0.17 fm^{-3}$ for all nuclei, for the skin parameter we use $a = 0.55 fm$ for A>16, $a = 0.43 fm$ for A$\leq$16.
5. **For INC Models**

   Relativistic kinematics is applied, with accurate conservation of energy and momentum, and with inclusion of the recoil energy and momentum of the residual nucleus.

   Binding Energies (B.E.) are obtained from mass tables, depending on particle type and on the actual composite nucleus, which may differ from the initial one in the case of multiple particle emission.

   All particles are transported along paths which are subject to curvature in the Coulomb and nuclear potentials. In this way, refraction and reflection at the nuclear surface are taken into account, and the Coulomb effects are properly described. The potential used for nucleons has been found to have a strong influence on the results. Energy dependent as well as constant potentials with different depths and radial profiles can be managed by the model. At the moment, the standard one, used in these simulations is essentially the Fermi potential.

   For pions, a nuclear potential has been calculated starting from the standard pion-nucleus optical potential.

   Path lengths and interaction mechanisms for all particles transported are chosen depending on particle-nucleon cross sections and local density.

   A rejection method is applied to take into account the dependence of the center of mass energy, and correspondingly of the cross section, on the actual momentum of the struck nucleon. The latter is, in turn, chosen according to a local Fermi distribution. All secondary nucleons are required to satisfy the Pauli exclusion principle; if they don't, the interaction is rejected.

   Mechanisms other than Pauli blocking which could be effective in increasing the particle mean free path in nuclear medium have been investigated and implemented. These mechanisms are important to prevent the well known problems met by INC codes including refraction and reflection because of strong secondary absorption in the nucleus core. The following mechanisms are implemented:

   - The formation zone concept after pion or nucleon inelastic (pion production) interactions
   - Nucleon antisymmetrization effects
   - Nucleon-nucleon hard-core correlations. Typical hard-core radii used are in the range 0.5-1 fm
   - "Coherence" length after elastic or charge exchange hadron-nucleon scatterings

Nucleon-nucleon total cross sections, both elastic and inelastic, are taken from available experimental data. Elastic scattering is explicitly performed according to the experimental differential cross sections.

Pions are fully trasported and are supposed to undergo elastic, charge exchange and inelastic scattering on nucleons, and two or three-body absorption following Oset et al.[26].

Inelastic hadron-nucleon scattering (pion production) is handled by an improved version of the HADRIN [21] model through the formation and decay of resonances.

6. **If there is a precompound phase, describe the PE model used, parameters,i.e. partial state densities, transition rates ?**

   Precompound following the Geometry Dependent Hybrid Model of Blann et al[27].

   Ericson exciton densities with restricted hole energy for low-number configurations.

   Transition rates from Fermi and Pauli-corrected n-n cross sections, with correlation/coherence corrections as in the INC part.

   Are clusters, multiple PE decay, relativistic kinematics used?

   No clusters.

   Multiple PE decay and relativistic kinematics included

   How are angular distributions computed ?

   Angular distribution following the fast particle approximation as implemented by Akkermans *et al.* [28]. Re-definition of the reference axis after particle emission. Isotropic distribution if the residual momentum is comparable with the average Fermi one. Free nucleon-nucleon smeared by Fermi momentum if the particle is emitted in the first interaction.

   Source of inverse cross-sections?

   Inverse cross section fitted to available experimental data.

7. **What physics are used for the final de-excitation stage: evaporation model, Fermi breakup ?**

   Evaporation model in competition with fission . Evaporation is based on an improved version of EVAP-5 [7], fission on the model by Atchison.

   Describe parameters used: level densities, inverse cross-sections or transmission coefficient, choice of optical model parameters if relevant (or reference to source), range of excitation allowed, inclusive or exclusive results?

   Level densities A and Z dependent, Ignatyuk [29] high temperature behaviour

   Inverse cross sections as in 6.

   Relativistic kinematics

8. **Is there any limit as to the number of nucleons from target for which yelds may be calculated?**

   No limit.

9. **Any other comment on aspects not considered in the above questions?**

10. **References to the literature or reports discussing these codes as implemented?** More detailed description of the code can be found in the references cited in I.4. Other examples of benchmarks and applications of FLUKA can be found in refs.[19, 20]

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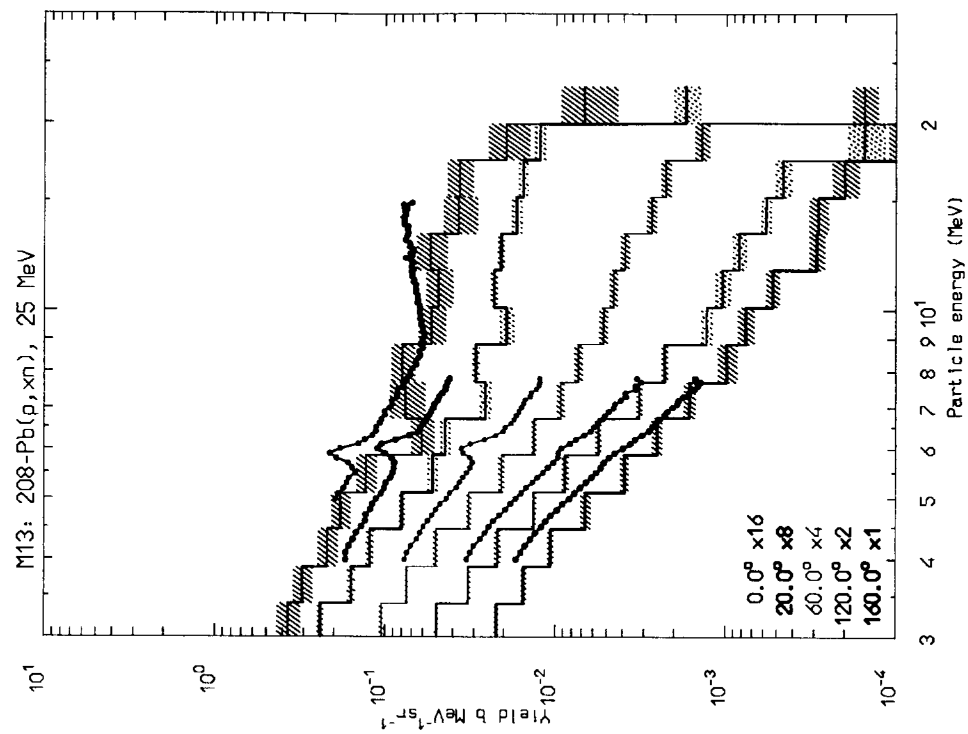

Figure 1: **208-Pb(p,xn), 25 MeV: DDCS**

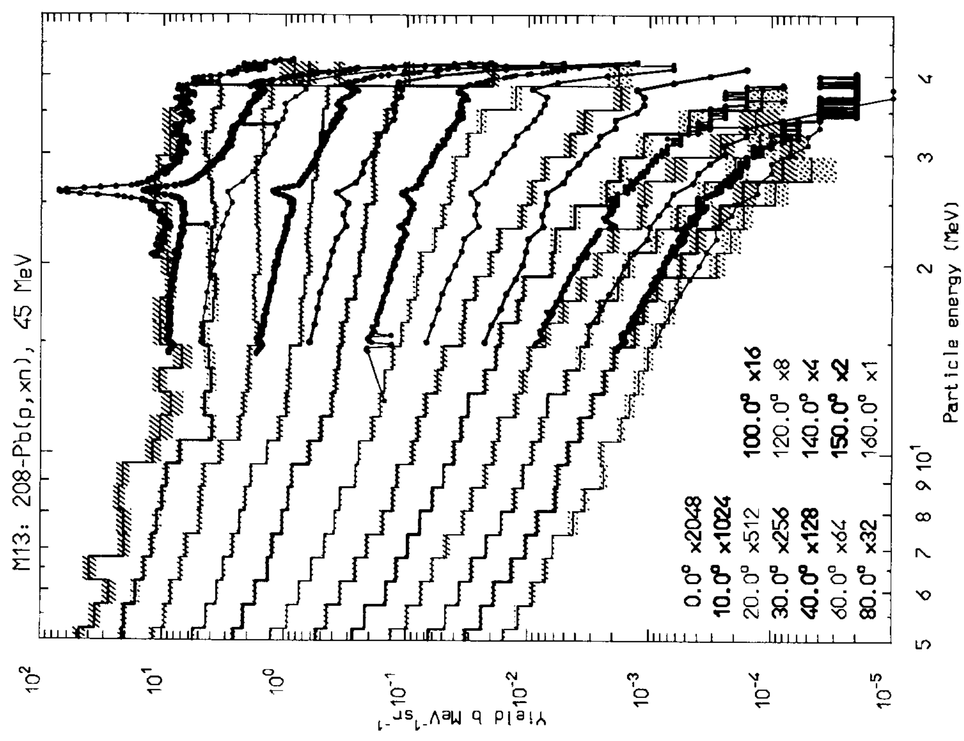

Figure 2: **208-Pb(p,xn), 45 MeV: DDCS**

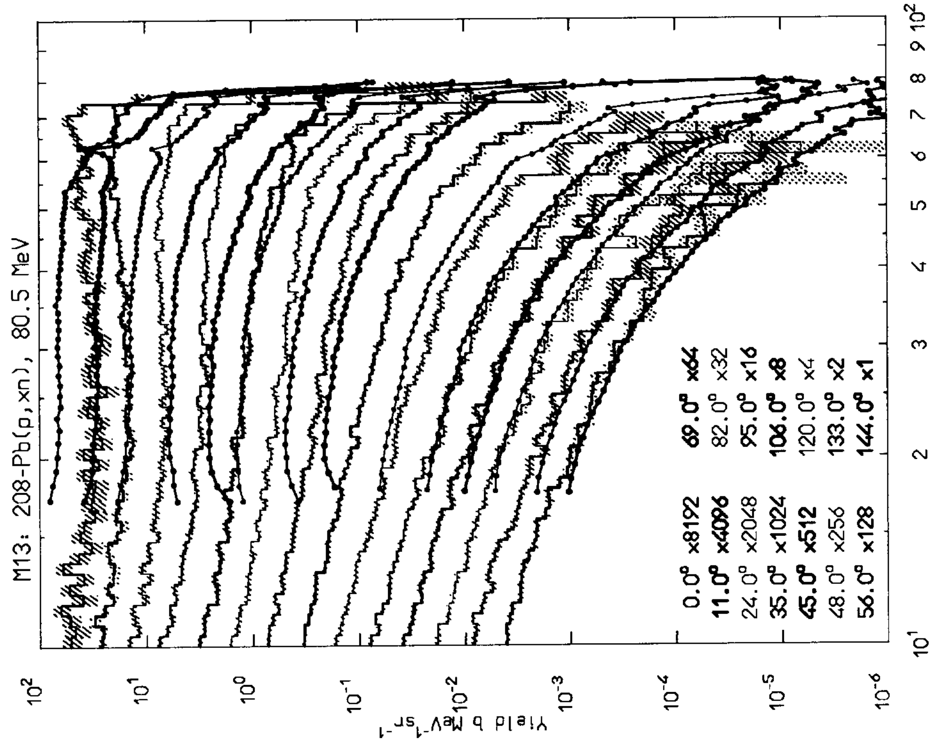

Figure 3: **208-Pb(p,xn), 80 MeV: DDCS**

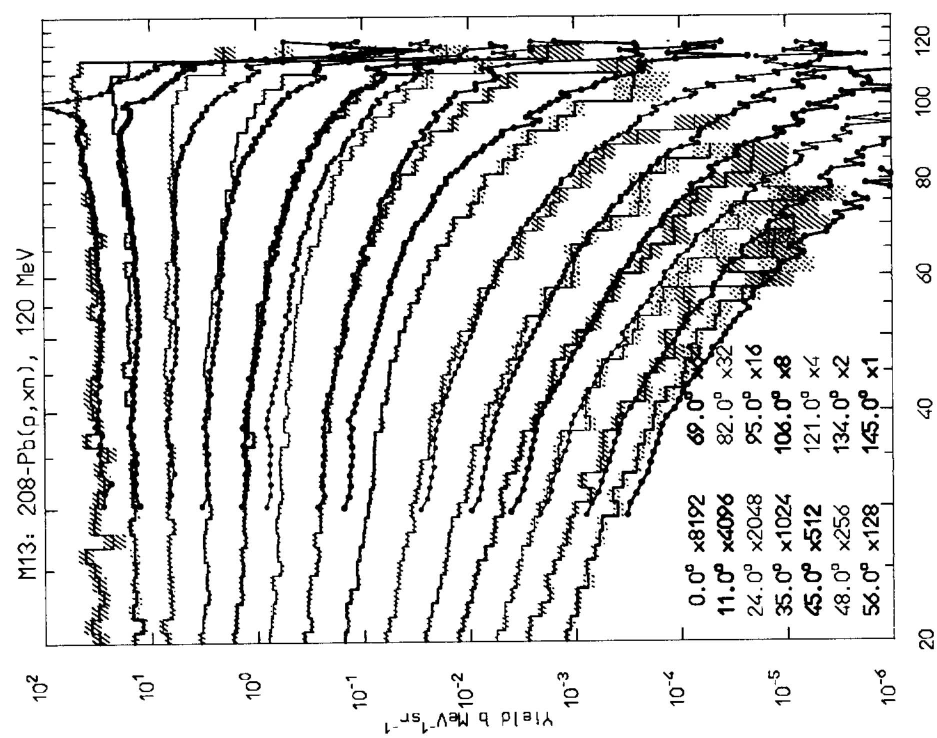

Figure 4: **208-Pb(p,xn), 120 MeV: DDCS**

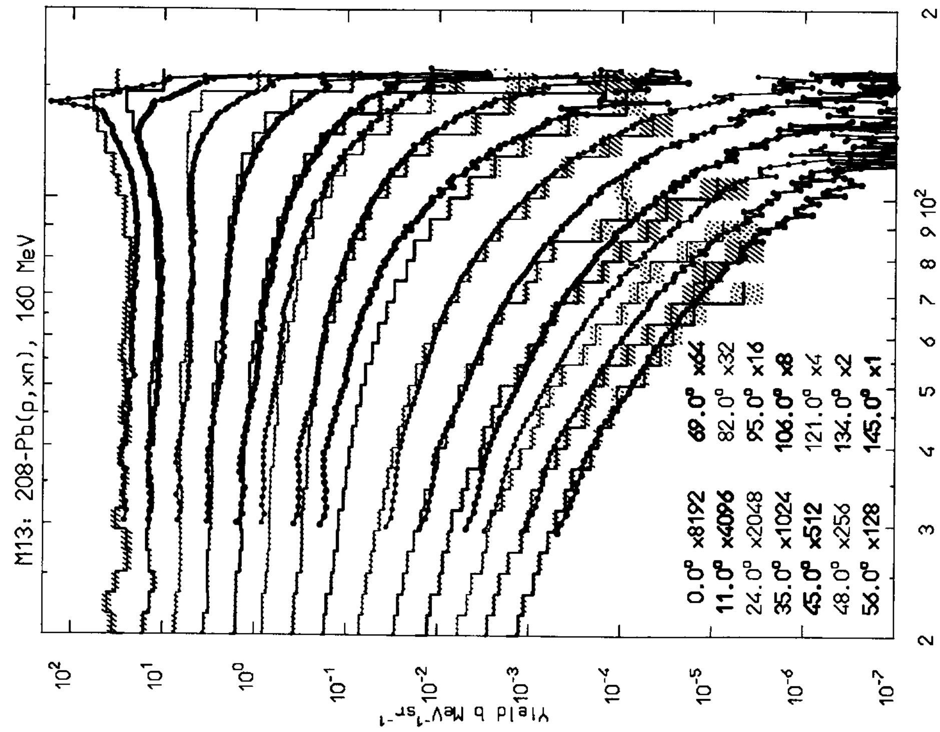

Figure 5: **208-Pb(p,xn), 160 MeV: DDCS**

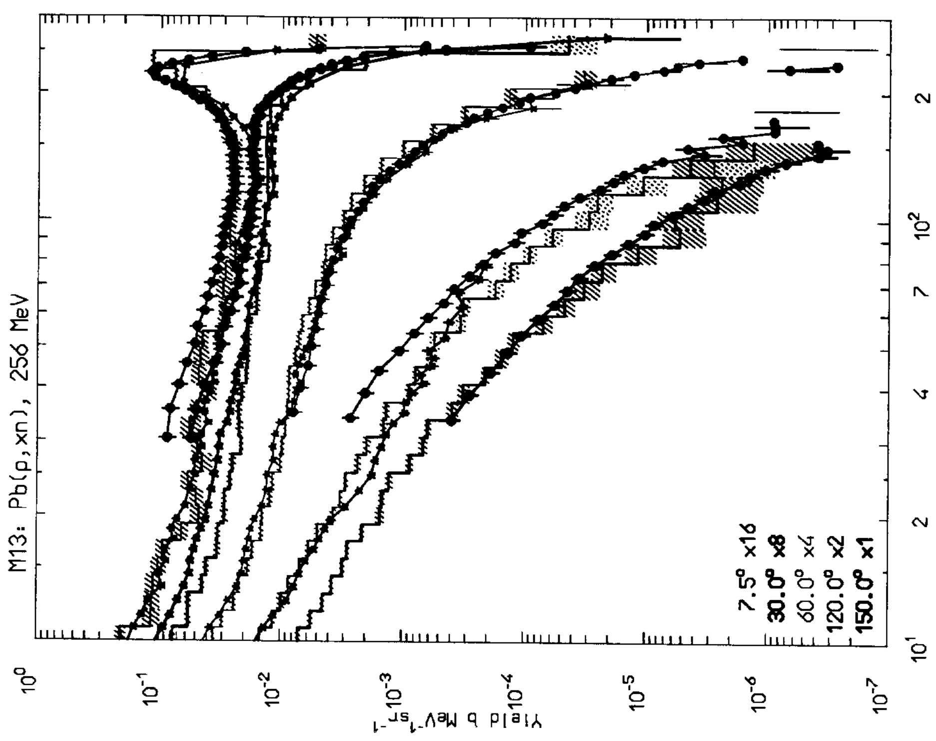

Figure 6: **Pb(p,xn), 256 MeV: DDCS**

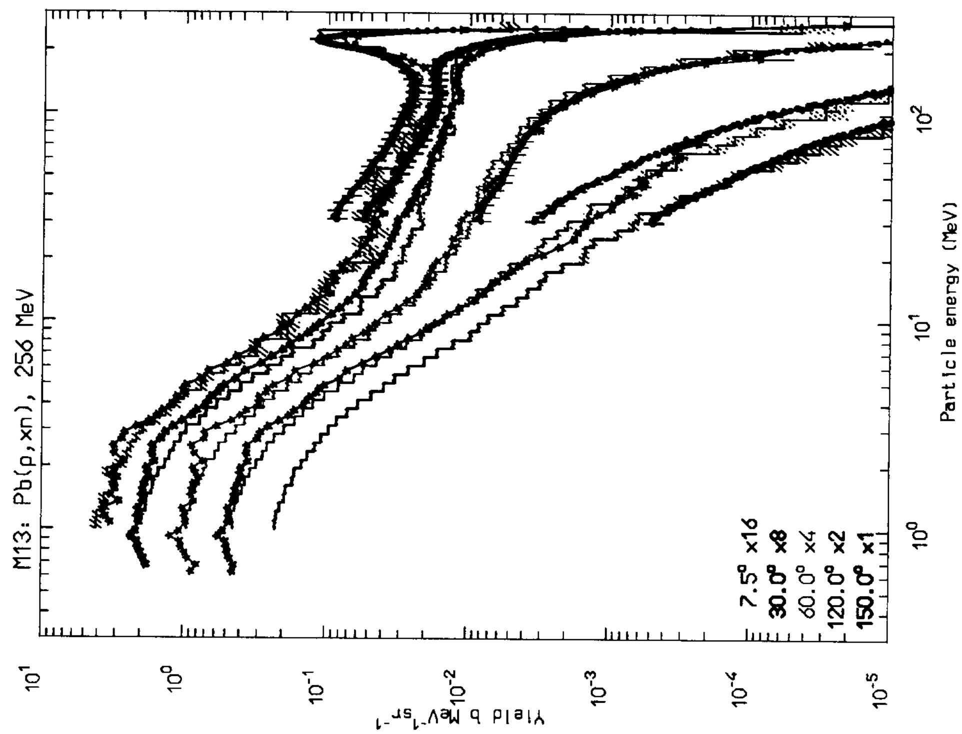

Figure 7: **Pb(p,xn), 256 MeV: DDCS**

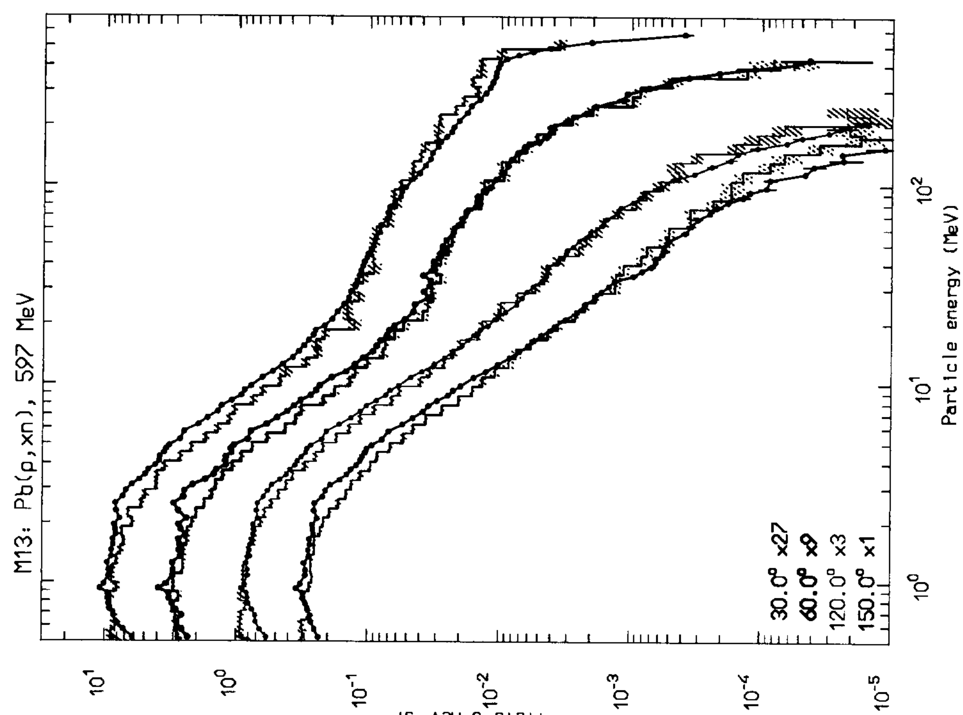

Figure 8: **Pb(p,xn), 597 MeV: DDCS**

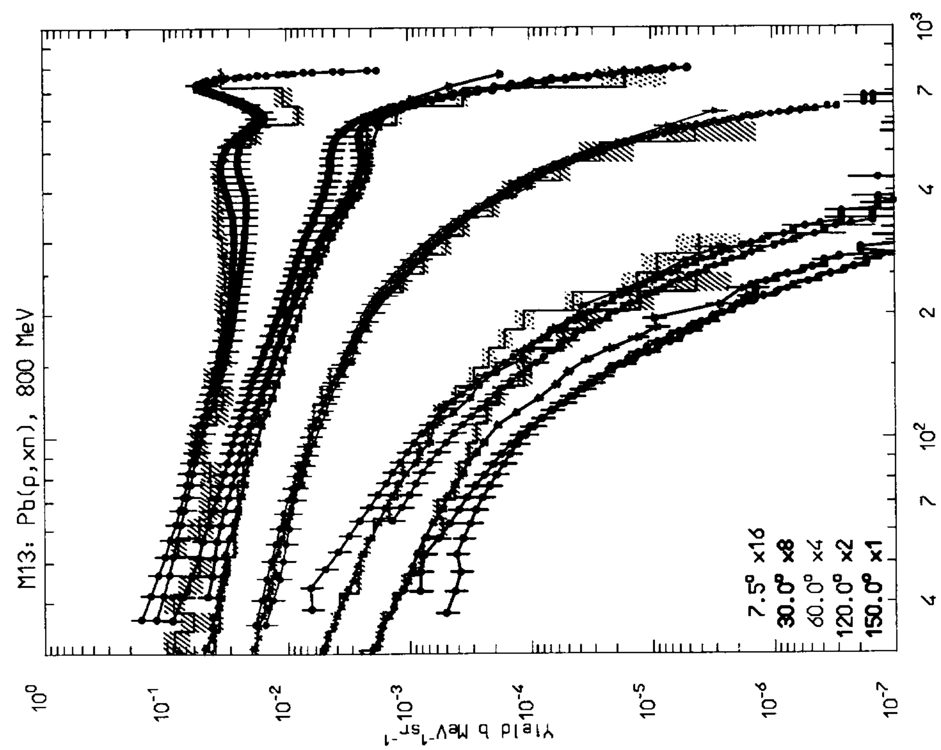

Figure 9: **Pb(p,xn), 800 MeV: DDCS**

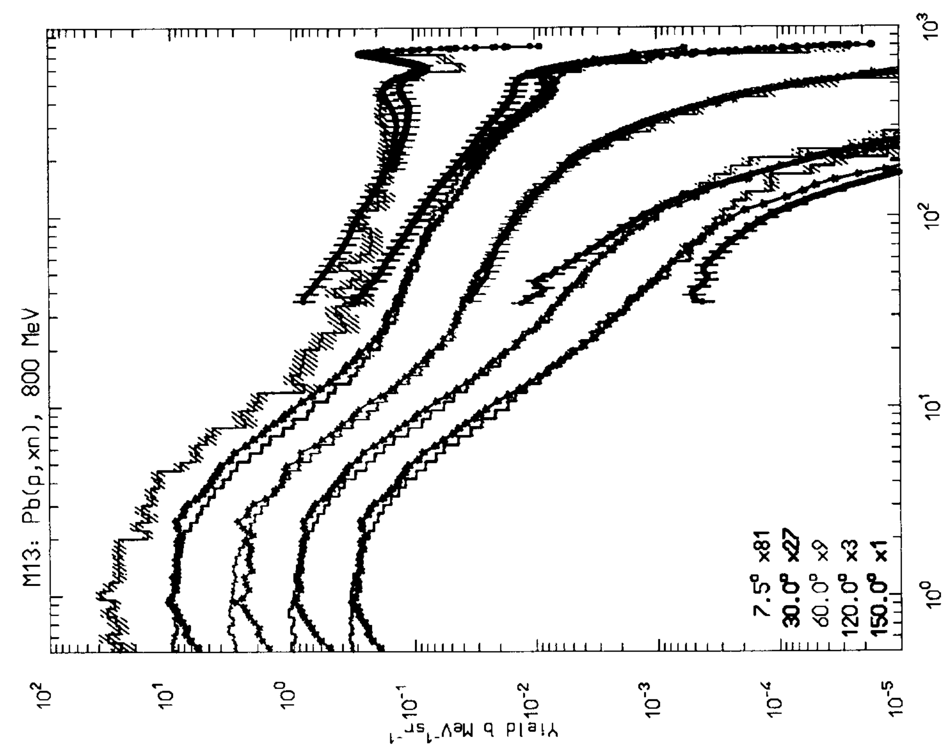

Figure 10: **Pb(p,xn), 800 MeV: DDCS**

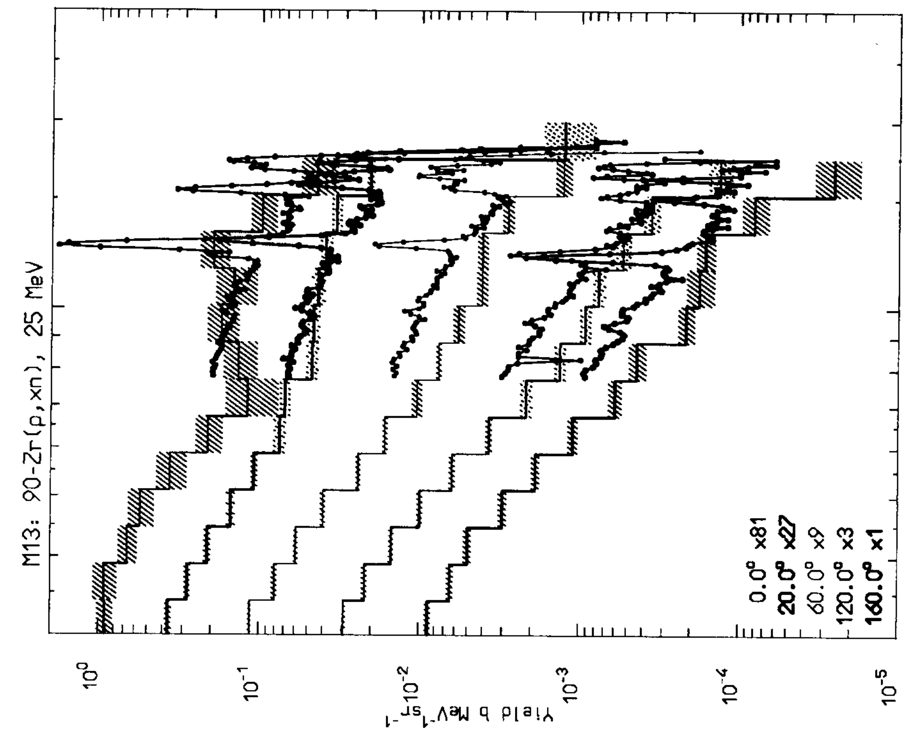

Figure 11: **90-Zr(p,xn), 25 MeV: DDCS**

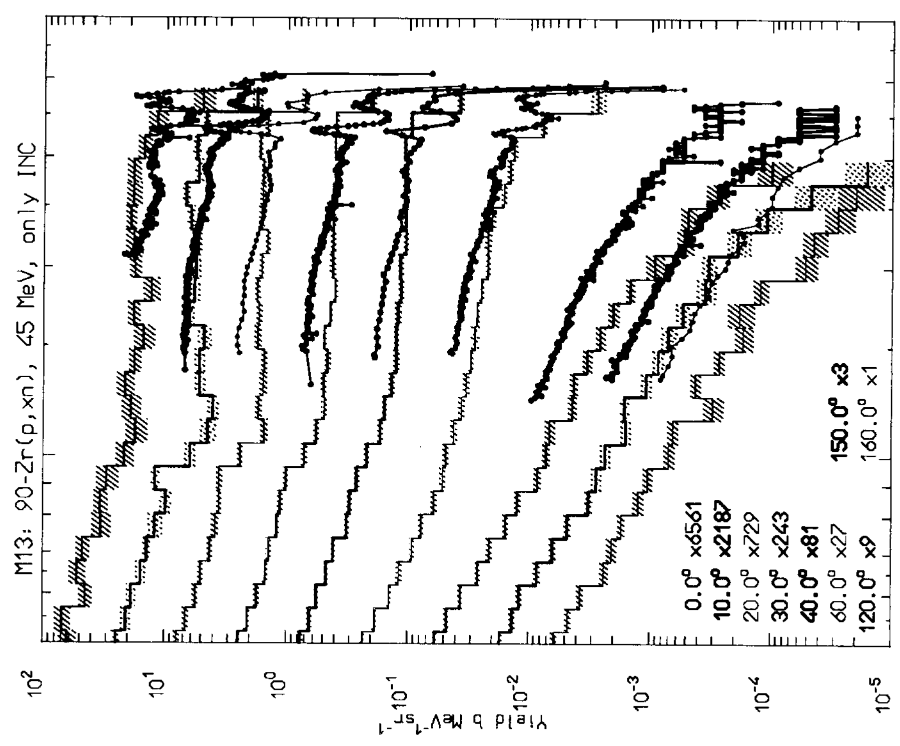

Figure 12: **90-Zr(p,xn), 45 MeV: DDCS**

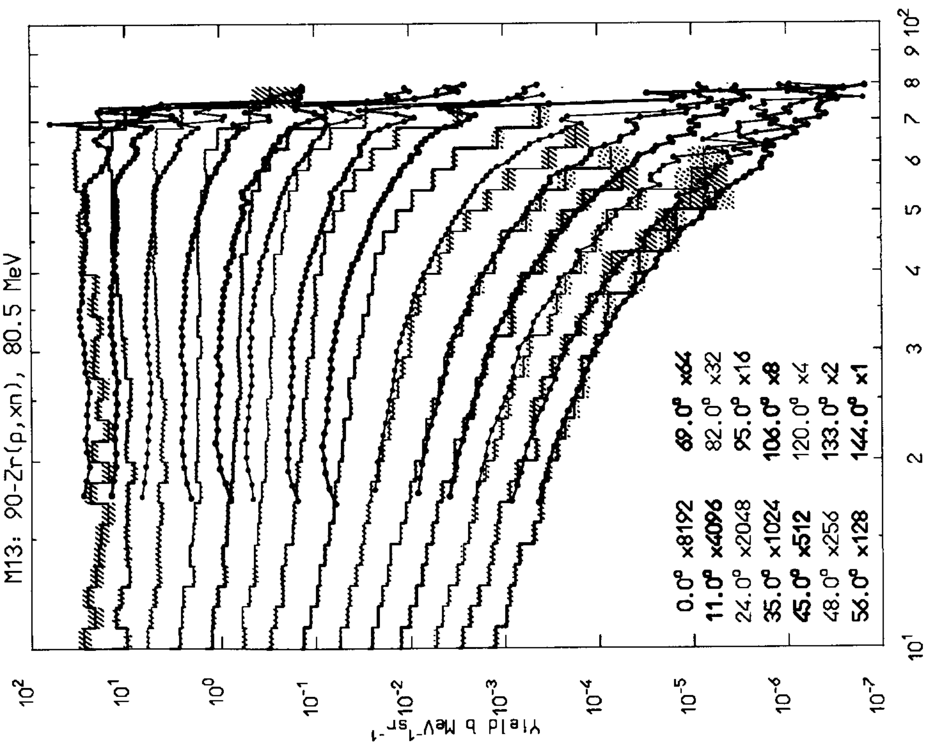

Figure 13: **90-Zr(p,xn), 80 MeV: DDCS**

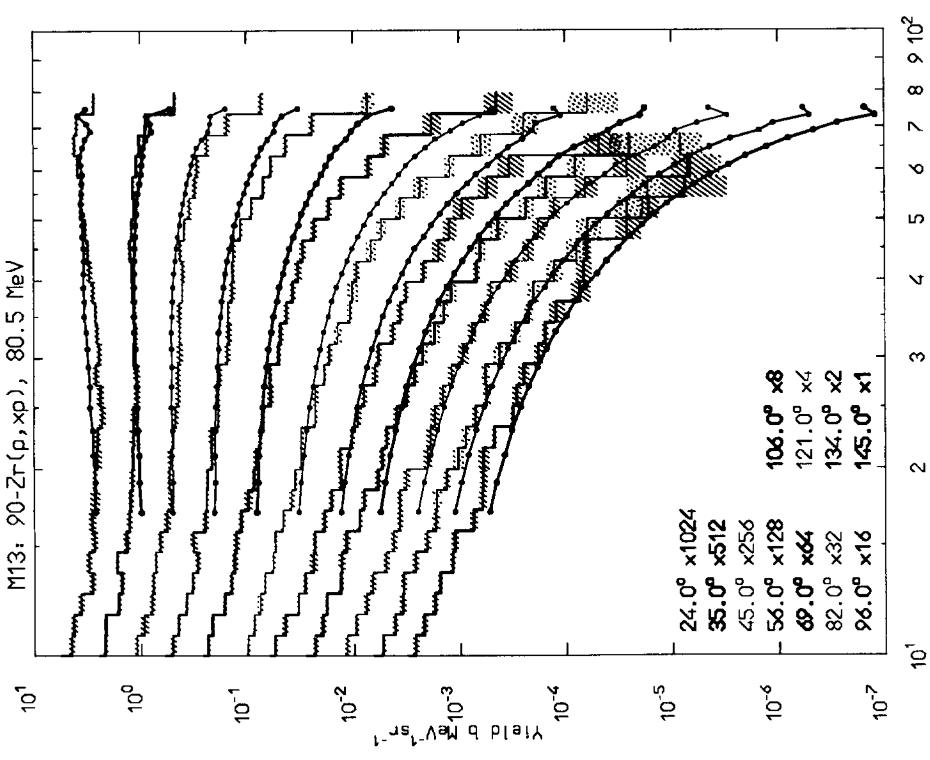

Figure 14: **90-Zr(p,xp), 80 MeV: DDCS**

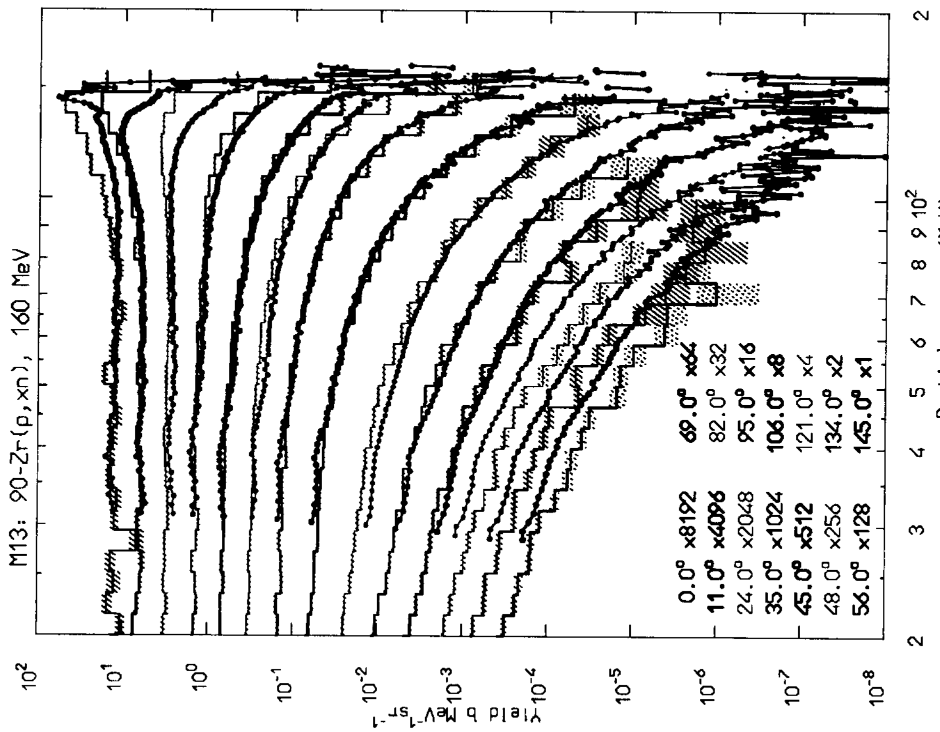

Figure 15: **90-Zr(p,xn), 160 MeV: DDCS**

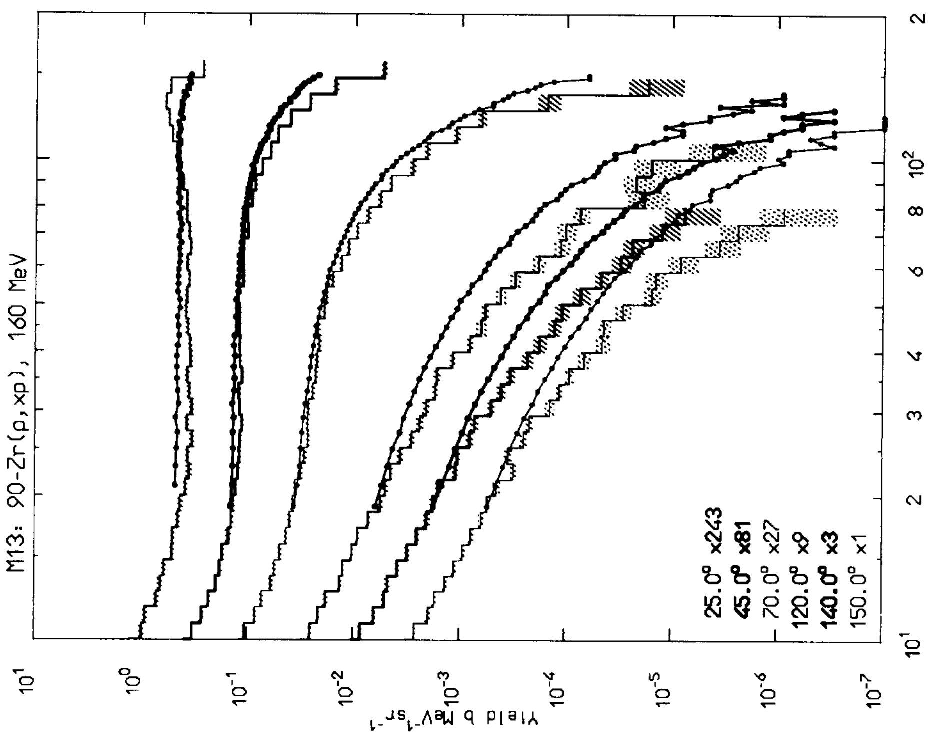

Figure 16: **90-Zr(p,xp), 160 MeV: DDCS**

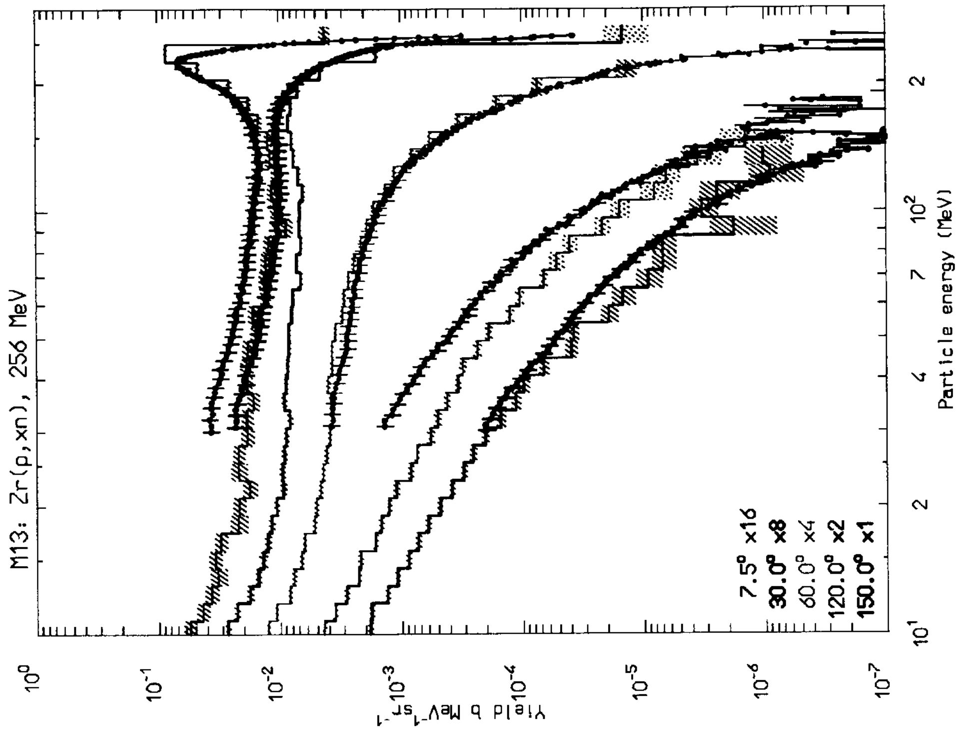

Figure 17: **Zr(p,xn), 256 MeV: DDCS**

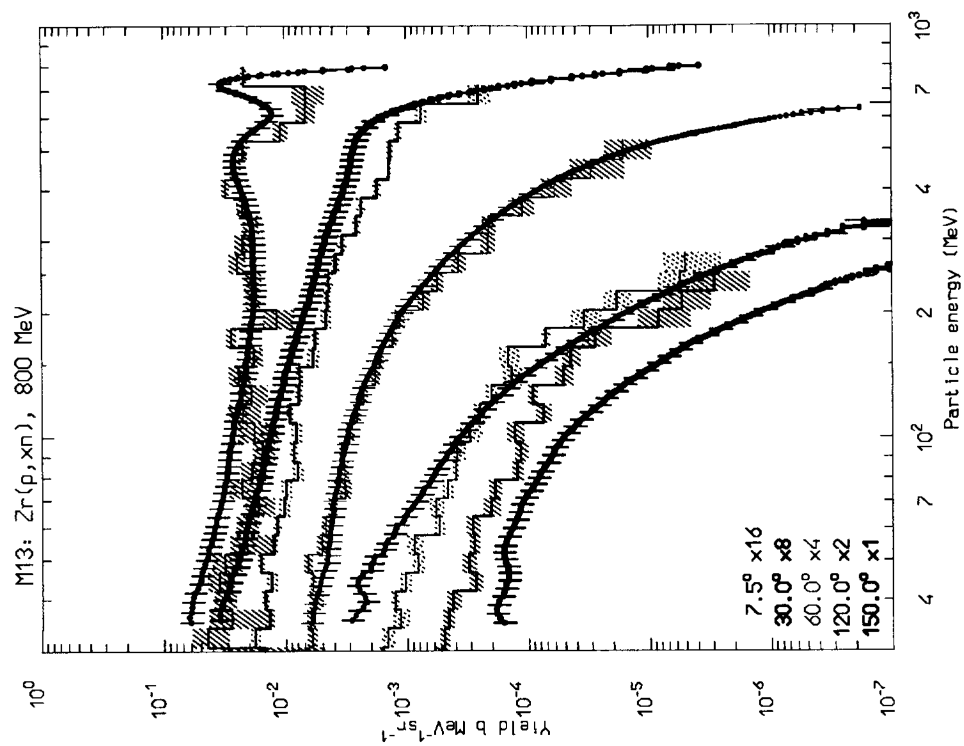

Figure 18: **Zr(p,xn), 800 MeV: DDCS**