Generation of Neutron Sources in Proton-Induced reactions in the Energy Range of 0.1 to 1 GeV

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Abstract

In this paper the generation of the neutron source in the proton transmission at the incident energies from 0.1 to 1 GeV and various targets (from ^{12}C to ^{238}U) is described.

In the frame of the Moving Source (MS) model the analysis of double differential spectra and multiplicities of nucleons, obtained in the primary proton-induced reactions on various targets in the incident energy range of 0.1 to 1 GeV, is carried out. Experimental data parametrization and extension of the MS model to the description of both (p,n) and (p,p') - reactions are worked out. In the (p,p') data analysis the quasi-elastic scattering was taken into account. It was found out that the contribution of the neutrons from the secondary proton -induced reactions is less than 10% of the total neutron yield. Parametrization of the inelastic cross section, with regard for π - meson production effect, was carried out.

To describe the proton transmission and the generation of the neutron source the MS model and Bethe stopping theory with relativistic corrections for protons were applied.

1.Introduction.

Production of intensive neutron sources by medium energy proton accelerators are of considerable interest because of manifold applications, to transmuting of long lived radioactive nuclides in particular.

In this paper the analysis of the double differential spectra and multiplicities of nucleons obtained in the proton-induced spallation reactions on various targets (from ^{12}C to ^{238}U) in the incident energy range of 0.1 to 1 GeV is carried out. Experimental data parametrization and extension of the MS model (*Moving Source* model) [2] to the description of both (p,n) and (p,p') - reactions are worked out. In the (p,p') data analysis the quasi-elastic scattering was taken into account.

It was found out that the contribution of the neutrons from the secondary proton -induced reactions is less than 10% of the total neutron yield. Parametrization of the inelastic cross section, with regard for π - meson production effect, was carried out.

To describe the proton transmission and the generation of the neutron source the code SOURCE was designed. This code is based on the MS model formalism and Bethe stopping theory with relativistic corrections for protons. It allows the estimations of the proton range, the changes of the proton current and the neutron production versus the depth.

The code SOURCE generates the input data for the MCNP code (for 3b- and 4- versions), simulating the set of single neutron sources, produced in the sample during the proton transmission. It permits one to make the complete analysis of the neutron transmission in the samples of arbitrary shapes with constituent substance.

In the last two decades a lot of experimental data on the proton-induced reactions in the incident energy range from MeVs to GeVs was accumulated. The existing rigorous theoretical approaches and models allow the estimation of various characteristics of these reactions, but they have uncertainty in choice of free parameters, the calculations are time-consuming, and their application entails much difficulties.

To describe the double differential inclusive nucleon spectra in spallation reactions, the phenomenological MS model was suggested in [1]. An important advantage of the MS model as a phenomenological one is that it is in a good agreement with experimental data. It uses relatively small number of free parameters, on the one hand, and is simple, on the other. It is easy to deduce important integral characteristics (such as total inclusive cross section, the secondary particle multiplicities) in the frame of the MS model. Moreover, this model is applicable both for engineer calculations and for scientific researches: for the estimations of contributions of various processes in nuclear reactions (equilibrium, preequilibrium, and cascade processes).

It was assumed in the MS model that the major processes, forming the spallation reaction nucleon spectra are cascade nucleon emission (1), preequilibrium emission (2), and evaporation (3). The inclusive nucleon spectra are obtained by summation of contributions of these processes:

$$\frac{d^2\sigma}{dEd\Omega} = \frac{d^2\sigma_1}{dEd\Omega} + \frac{d^2\sigma_2}{dEd\Omega} + \frac{d^2\sigma_3}{dEd\Omega} \tag{1}$$

In this model nucleons were assumed to be emitted isotropically from a single moving source for each process with an exponential form

$$E_{tot}\frac{d^3\sigma}{dp^3} = Aexp\left\{-\frac{E^*}{T}\right\} \tag{2}$$

in the frame of the source, moving with the velocity β relative to the laboratory frame. The velocity and temperature T are the free parameters, adjusted to fit the experimental data. E^* is the secondary particle kinetic energy (MeV) in the single moving source frame, E_{tot} is the total energy, the sum of the rest mass m and kinetic energy $E^2_{tot} = m^2c^4 + p^2c^2$. The Lorentz transformation to the laboratory frame gives a Maxwell-like kinetic energy distribution

$$\frac{d^2\sigma_i}{dEd\Omega} = A_i pexp\left\{-\left(\frac{E+m-p\beta_i cos\Theta}{\sqrt{1-\beta_i{}^2}} - m\right)/T_i\right\}, \quad i = 1,2,3, \tag{3}$$

where E, p, Θ are the kinetic energy, momentum, and emission angle in the laboratory frame.

Three parameters are required in the model to specify each component of the spectrum. These parameters may be treated as amplitude A_i, temperature T_i, and velocity of the single moving source β_i. The parameters A_i, β_i, T_i $(i = 1,2,3)$ are adjusted to fit experimental data. This allows one to take into account the nucleons, emitted from all spallation reaction fragments.

The MS model was utilized in [2] for creation of systematics of the neutron spectra from the proton-induced spallation reactions to describe inclusive double differential neutron cross sections for the incident range of 0.1 to 1 GeV. Target nuclear mass A_M dependencies of parameters for the incident energy points 113 and 585 MeV and incident energy dependencies for lead were suggested. The choice of these energy points is due to the wide range of the experimental data for various nuclei.

The mass number and the energy parameter dependencies are listed in Table 1.

Table 1. Systematic of the MS model parameters from [2].

N	A, $mb/sr/MeV^2/c$	T, MeV	β
1a	$0.00179 \times A_M{}^{0.408} - 0.00427$	76.2	$-0.000281 \times A_M + 0.268$
2a	$0.000281 \times A_M$	$0.0258 \times A_M + 15.6$	0.0648
3a	$0.000216 \times A_M{}^2 + 0.0750$	$0.000864 \times A_M + 2.36$	$0.0183 \times e^{-0.00848 A_M}$
1b	$0.00510 \times A_M + 0.00858$	16.5	$-0.000281 \times A_M + 0.238$
2b	$0.000359 \times A_M - 0.00065$	$0.00701 \times A_M + 6.73$	0.00559
3b	$0.000298 \times A_M{}^2 - 0.0395$	$-0.00278 \times A_M + 2.06$	$0.0878 \times A_M{}^{-.700}$
1c	$-0.0000112 \times E_p + 0.0165$	$0.106 \times E_p + 4.0$	$0.00012 \times E_p + 0.160$
2c	$-0.0000238 \times E_p + 0.0864$	$0.0255 \times E_p + 5.54$	$0.000098 \times E_p - 0.00666$
3c	$-0.00939 \times E_p + 13.1$	$0.00238 \times E_p + 1.08$	$0.00000376 \times E_p + 0.00119$

In this table N is the process number: (1),(2),(3) correspond to the cascade, preequilibrium, and evaporation neutron emission, respectively. Index references to the set of parameter dependencies for the incident energy points 585 MeV (a), 113 MeV (b), and for lead (c).

It was pointed out in [2] that it is necessary to introduce the Watt distribution into the MS model to reproduce the high-energy neutron spectra for the incident energy less than 300 MeV. The cascade cross section in the laboratory frame is written as

$$E_{tot}\frac{d^3\sigma_1}{dp^3} = \frac{A_W}{p^*}exp\left\{-\frac{E^*}{T_W}\right\} \times sinh(2\sqrt{E^* E_W}/T_W). \tag{4}$$

Energy E^* and momentum p^* in laboratory frame are expressed by $E^* + m = (E + m - p\beta cos\Theta)(1-\beta)^{-1/2}$, $p^* = (E^{*2} + 2mE^*)^{1/2}$. The parameters T_W and E_W are designated Watt-moving-source temperature and energy, respectively, and are converted into the temperature parameter T' of the Maxwell distribution as $T_1' = T_W + 2/3E_W$. Parameter A_W is converted into equivalent amplitude parameter A_1' as $A_1' = A_W(E_W + 3/2E_W + m)^{-1/2}$.

Target mass dependencies of the parameters, suggested in [2], are assumed to be as follows:

$$\begin{aligned} A_W(A_M) &= 0.00510 \times A_M + 0.00852 \\ E_W(A_M) &= -0.0119 \times A_M + 13.1 \\ T_W(A_M) &= 0.00701 \times A_M + 6.73 \end{aligned} \tag{5}$$

Taking into account the results from [2], where the principle possibility of approximation of the parameters by a smooth function was shown, we obtained the parameters as a function of target mass and incident energy.

Assuming the energy dependence for all nuclei to be linear, as for lead, it is easy to restore the energy dependence for each nuclei, referring to the energy points 113 and 585 MeV. But the energy dependencies of cascade amplitude parameter, obtained by means of this procedure, has essential restrictions on the incident energy: for $A_M > 137$ there is a maximal incident energy (at energies beyond this one parameter A_1 becomes negative); varies from 600 to 900 MeV with changing A_M.

In this paper the amplitude parameter energy dependence for the cascade process is assumed to be linear for all nuclei, excluding ones with mass $A_M < 12$ and $A_M > 137$, where energy dependence of A_1 is expressed by $C_1 {E_p}^2 + C_2 E_p + C_3$, and

$$\begin{aligned} C_1 &= (0.0304 A_M - 2.12) \times 10^{-8} \\ C_2 &= (-0.0482 A_M - 2.24) \times 10^{-5} \\ C_3 &= (0.215 A_M - 1.957) \times 10^{-3} \end{aligned} \tag{6}$$

For an example, the double differential neutron spectra in $^{184}W + p$ reaction, calculated in the frame of this systematics for the angles $30^o, 90^o, 150^o$ and the incident energy $E_p = 800$ MeV, are displayed in Fig.1.

The choice of this reaction is due to the fact, that the estimation of the secondary particle spectra and multiplicities of nucleons in the reactions $^{184}W + p$ are of special interest.

2.consideration of quasi-elastic scattering in (p, p') - reactions, extension of the MS model to (p, p') - reaction description.

In [3] the MS model was applied for the calculations of proton inclusive spectra in the (p, p') - reactions in the incident energy range of 1 to 10 GeV. The emphasis was on the possibility of the secondary proton spectra parametrization in the MS model frame, and the attempt of building up of systematics analogous to [2] for estimation of the cascade proton spectra was made.

To make a correct analysis of experimental data on (p, p')- reactions for a wide range of the secondary proton angles and energies (especially for forward angles and high-energy regions of spectra), it is necessary to take into account the direct, elastic and quasi-elastic processes. The simple estimations show that the contribution of direct processes dominates the contributions of other processes when the angles are less then 5^o. Quasi-elastic scattering dominates the inclusive spectra for scattering angles in the laboratory frame less than 30^o. The role of elastic scattering of medium-energy protons is small. This paper concerns the description of the spectra in the angle range of 7^o to 180^o.

As it was pointed out in [11] at the incident energy range of 60 to 200 MeV the quasi-elastic scattering comprises from 60% to 80% of the reaction cross section in medium and medium-heavy nuclei and about 50% in heavy nuclei. Its contribution into the inclusive spectra increases with the incident energy.

The developed rigorous theoretical approaches and models (for example Glauber theory) allow the calculations of various characteristics of quasi-elastic processes, but it seems us preferable to carry out the calculations in the frame of unified approach.

In this paper the quasi-elastic peak is fitted by Gaussian function (by analogy with [16], where the proton spectra were analyzed for the incident energy 660 MeV):

$$\frac{d^2\sigma_{qel}}{dEd\Omega} = A_{qe} exp\left\{ -\left(\frac{E_{p'} - E_0}{2\sigma} \right)^2 \right\}, \tag{7}$$

A_M is the target mass, $E_{p'}$ is the secondary proton energy. We suggest the approximation formulas for A_{qe}, E_0, σ to be as follows:

$$\begin{aligned} \frac{E_{p'}}{E_0} &= 0.0931 + 7.78 A_M \ 10^{-3} - 9.41 A_M^2 \ 10^{-4} + 1.42 A_M^3 \ 10^{-5} \\ A_{qe} &= 48.704 \Theta^{-1.876} A_M^{0.4} \end{aligned}$$

$$\sigma = 0.0153\ \Theta\ E_{p'}{}^{0.176}$$

Here Θ is the angle in laboratory frame, expressed in degrees. The target mass dependence of the parameter A_{qe} was chosen considering the results of the analysis from [17] to be $A_{qe} \propto A_M^{0.4}$.

Fig.2 demonstrates the comparison of the calculated proton spectra in $^{27}Al(p,p')$ and $^{209}Bi(p,p')$ reactions for the incident energy $E_p = 450$ MeV with experimental data. The results of calculations satisfy the experimental data.

The parameters A_{qe}, E_0, σ were found from experimental data with a least-squares-deviation procedure. The experimental data were taken from the follows Refs.: 90,200 MeV - [7], 450 MeV - [13] ,660 MeV - [16].

To build up the systematics of the parameters A, β, T for proton spectra we have analyzed a wide range of experimental data on (p,p') - reactions for the incident energy range of 0.1 to 1 GeV. The parameters A, β, T were fitted to the experimental data with a least-squares-deviation procedure.

To fit the parameters A, β, T, we proceed on the following assumptions:

1. the protons emitted in the cascade reactions have the energies above 60 MeV [4];
2. the elastic processes were not considered;
3. the evaporation proton contribution is negligible for the secondary proton energies above 20 MeV [5].

A brief information on the references, where the (p,p') - reaction data systems were presented, is listed in Table 2: the incident energy, the ranges of the ejectile energies, and angles and references.

Table 2. Data for (p,p') reactions.

Target	Incident Energy $E_{p'}$,MeV	Energy range $E_{p'}$, MeV	Angle range $\Theta_{p'}$, deg.	Ref.
$^{27}Al-^{209}Bi$	90	15-80	20-140	[7],[8],[9]
$^{27}Al-^{208}Pb$	164	35-140	25-150	[10],[11]
$^{27}Al-^{197}Au$	200	10-190	14-135	[10],[11],[12]
$^{9}Be-^{209}Bi$	450	130-450	30-60	[13],[12]
$^{27}Al-^{184}Pb$	558	50-530	10-60	[10]
$^{27}Al-^{181}TA$	600	200,340	30-152	[10]
^{12}C	640	60-145	180	[15]
^{64}Cu	730	40-150	30-120	[3]
$^{64}Cu-^{208}Pb$	740	30-220	90-135	[4]
^{64}Cu	1730	40-150	30-60	[3]
$^{12}C-^{208}Pb$	3170	40-150	30-60	[3]

Figs. 3,4 display energy parameter dependencies of preequilibrium and cascade processes for Al and Pb and target mass parameter dependencies for the incident energies 90, 450, 740, and 3170 MeV. Points denote the results of fitting of the parameters to the data set for concrete nuclei, and lines represent the results of parameter approximation.

The suggested MS model parameter systematics for the proton spectra calculations are listed in Table 3.

Figs. 5,6 display the comparison of the calculated proton spectra in the reactions $^{27}Al+p$ and $^{208}Pb+p$ for the incident energy 90 MeV and 740 MeV with the experimental data, respectively. These figures demonstrate the good agreement with experimental data.

Table 3. Systematics of MS model parameters for (p,p') reactions.

N	A $mb/sr/MeV^2$	β	T, MeV
1a	$0.00329 \times A_M{}^{0.373}$	$-0.000274A_M + 0.247$	23.0
2a	$2.31310^{-5} A_M(1000. - A_M)e^{-0.02A_M}$	0.0143	$0.0225A_M + 3.22$
1b	$0.000448 \times A_M{}^{0.510}$	$-6.95110^{-5} A_M + 0.253$	54.0
2b	$0.45610^{-5} A_M(1000. - A_M)e^{-0.0218A_M}$	0.0397	$0.0147A_M + 5.58$
1c	$9.86 \times A_M{}^{0.838} 10^{-5}$	0.244	55.95
2c	$0.63810^{-5} A_M(1000. - A_M)e^{-0.0176A_M}$	0.0602	$0.0140A_M + 6.08$
1d	$7.840 \times A_M{}^{1.019} 10^{-5}$	$-0.000483A_M + 0.225$	58.00
2d	$2.15610^{-5} A_M(1000. - A_M)e^{-0.00623A_M}$	0.232	$0.00757A_M + 7.55$
1e	$0.326 \times E_p{}^{-0.811}$	$0.153 \times E_p{}^{0.0732}$	$4.076E_p{}^{0.421}$
2e	$0.0901 \times E_p{}^{0.0129}$	$5.09110^{-4} \times E_p{}^{0.722}$	$1.048lnE_p - 0.547$
1f	$0.0451 \times E_p{}^{-0.254}$	$0.296 \times E_p{}^{-0.0142}$	$8.443E_p{}^{0.308}$
2f	$1.39210^{-5} \times E_p{}^{1.455}$	$6.45810^{-4} \times E_p{}^{0.681}$	$0.326lnE_p + 6.631$

In Table 3 N is the process number: (1) corresponds to the cascade emission and (2) corresponds to preequilibrium emission. Index references to the set of parameter dependencies for the incident energies E_p = 90 MeV (a), E_p = 450 MeV (b), E_p = 740 MeV (c), E_p = 3170 (d), and for targets Al (e) and Pb (f).

The double differential proton spectra in $^{184}W(p,p')$ - reactions, calculated in the frame of these systematics for the incident energy E_p = 800 MeV, are shown on Fig.7.

3.Inelastic cross section analysis and nuclear multiplicities.

To describe the generation of the neutron source in the proton transmission it is necessary to estimate inelastic cross sections for the incident energies of 0.1 to 1 GeV and various targets (from ^{12}C to ^{238}U) is described.

Approximation equations, suggested in [6], can give an overall form of the energy dependence of σ_{in}, but phenomenological analysis of the experimental data in the region of 0.1 to 1 GeV is required to make them more precise.

The next approximation expressions are suggested:

$$\sigma_{in} = 44. \times A_M{}^{0.69}\left\{1 + \frac{1}{\sqrt[3]{A_M}}(Z + Z_\pi - 2)\right\}, \tag{8}$$

where the term Z_π considers the π - meson production effect.

$$Z = a_1 E_p^{-a_2} + a_3\left(\frac{e^x - 1}{e^x + 1} + 1\right), \qquad Z_\pi = A_\pi \times exp\left\{-\frac{(E_p - E_\pi)^2}{\omega^2}\right\}$$
$$x = a_4(E_p - a_5)$$

and

$a_1 = 19.301$ $\qquad A_\pi = 1.141 \times e^{0.002527A_M}$

$a_2 = 0.461$ $\qquad E_\pi = 730.43 - 0.296 \times A_M$

$a_3 = 0.860 - 1.033 \times 10^{-5}(A_M - 44.8)^2$ $\qquad \omega^2 = 31158.4 - 116.174 \times A_M$

$a_4 = 0.01$

$a_5 = 890.0$

The bump in the region of the incident energy $E_p \sim 600 \div 700$ MeV may be related with the π - meson production effect.

In [19] the nucleon-nucleon interaction at the energies from 500 to 2000 MeV was studied in the frame of "conventional" meson-theoretical model of the coupled NN and $nn\pi$ systems. It was shown that the contribution of $NN \rightarrow NN\pi$ processes is especially large around 600 MeV (the $N\Delta$ "threshold").

At the same time, the collective effects, the clusterization effects, in particular, in nuclei can lead to variations of attitude of the peak.

The threshold energy of particle production in nucleon-nucleus interactions in the relativistic case is given by

$$\epsilon = \left(1 + \frac{m_p}{M}\right)\mu + \frac{\mu^2}{2M}, \tag{9}$$

where m_p is the projectile mass, M is the mass of particle, cluster, or nucleus on which the π-mesons are being produced, μ is the sum of produced particle masses. Since the single π^o-meson production is suppressed (according to the parity conservation law), $\pi^+\pi^-$ and $\pi^o\pi^o$ production has a minimal threshold energy . The threshold energy decreases with nuclear mass.

Applying a least-squares-deviation procedure, we found the attitude of the peak for various nuclei to be as follows: ^{12}C – 726.9 MeV, ^{27}Al – 722.4 MeV, ^{64}Cu – 711.5 MeV, ^{208}Pb – 668.9 MeV.

Fig.8 demonstrates the comparison of the inelastic cross section, evaluated in the frame of these systematics, with the experimental data.

Applying this approximation formulas, one can easily estimate the total nucleon multiplicity: the number of the secondary nucleons per one interaction, expressed by ratio of the total inclusive cross section σ_n to the inelastic cross section σ_{in}:

$$M_n = \frac{\sigma_n}{\sigma_{in}} \tag{10}$$

The comparison of the results of our calculations with those obtained in [14] are shown in Figs. 9 b and 10 b. One can see that our results of estimation of nucleon multiplicities are close to the result from [14]. The proton and neutron multiplicities versus nuclear mass and incident energy are plotted in the Figs. 9 a and 10 a, respectively.

4.Generation of the neutron source.

The proposed method gives a simple procedure of obtaining of the secondary nucleon yields in the primary reaction with nucleus. Of practical interest is the estimation of the neutron production in nucleon transmission in the sample of arbitrary shape.

The transport Monte Carlo Code MCNP [18], using the data bank for calculations of neutron and photon interaction cross section, allows the calculations of the neutron and photon transmission in the sample of arbitrary shapes with constituent substance.

To describe the proton transmission and the generation of the neutron source the code SOURCE was designed. The code generates the input data for the MCNP code (for 3b- and 4- versions), simulating the set of single neutron sources, produced in the sample during the proton transport. The code is based on of the MS model formalism and Bethe stopping theory with relativistic corrections for protons. It allows the estimations of the proton range, the changes of the proton current and the neutron production versus the depth. It permits one to make the complete analysis of the neutron transmission.

The integral characteristics of the proton transmission and the neutron production are listed in the Table 4.

Table 4.

Substance	Density g/cm^3	Proton range, cm	Total number of neutrons	Average number of neutrons per proton
Fe	7.866	43.68	4441	4.83
W	19.29	23.34	10470	11.48
Pb	11.32	40.90	9511	10.44
Th	11.69	40.93	13374	14.65
U	19.04	25.28	13758	15.08

Fig.11 represents the examples of proton transmission analysis for various sample: ^{238}U, ^{184}W,

^{207}Pb, ^{232}Th, and ^{56}Fe. One can easily see from this figure, that the density of the sample material is a decisive factor in the proton transmission, on one hand, and that the neutron production depends both on the interaction cross section and the density, on the other hand. Thus the curve of dependencies of the proton average energy and the proton number from the depth for lead and thorium coincide (Figs. 11a and 11b). The neutron yield from ^{207}Pb, integrated over the depth, is less than one for ^{238}U, and the neutron yield from lead dominates the yield from uranium for depth beyond 8.5 cm (see. Fig.11 c). In the Figs. 11 a and 11 b the curves for thorium and for lead coincide.

It is necessary to point out that the average energy of the secondary protons in the primary reaction $^{184}W(p,p')$ for E_p = 800 MeV is about 50 MeV. As one can see from Fig. 11 b,c the secondary protons with such energies are being stopped rapidly. And their contribution into the neutron production is less than 10%.

5.Conclusions.

As the result of our analysis, we came to the next conclusions:

1) the density of the sample material is a decisive factor in the proton transmission;

2) the neutron production depends both on the interaction cross section and the density;

3) considering our estimations, the contribution of the neutrons from the secondary proton reactions makes up about 10% of the total yield of the neutrons, produced in the proton stopping processes. The neutron multiplicities and the double differential cross sections were estimated accurately up to 20% for the middle nuclei and more accurately for heavy nuclei.

5.Acknowledgments.

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Fig. 1

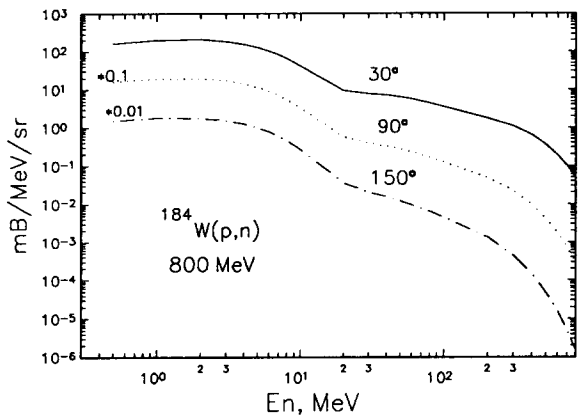


Fig. 2a

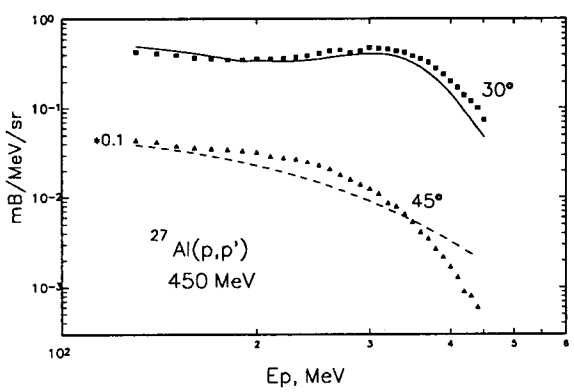
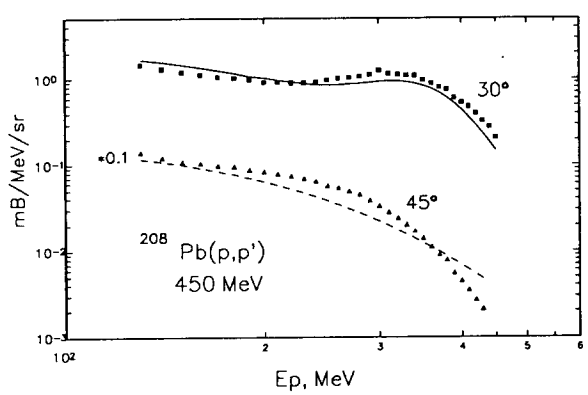
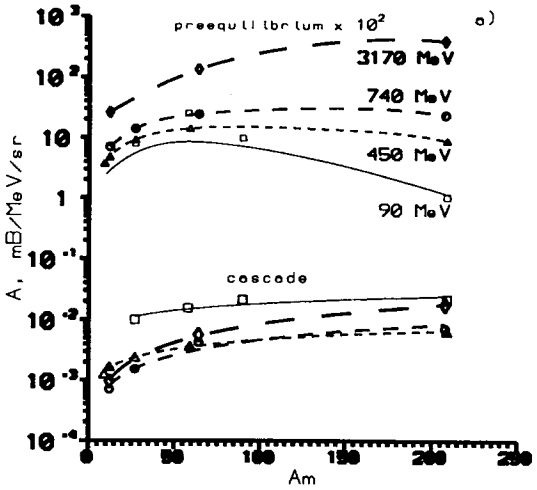
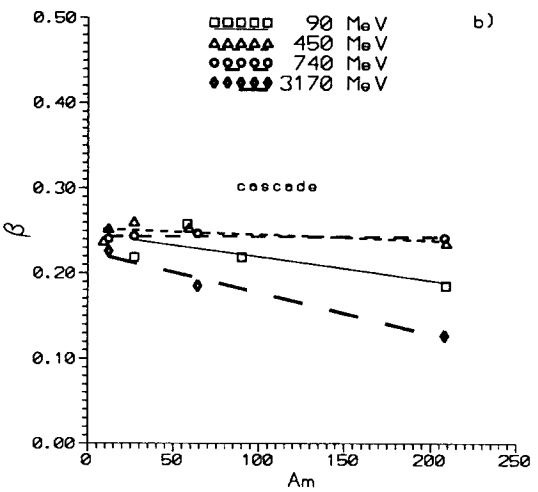


Fig. 2b




preequilibrium x 10²
a)
3170 MeV
740 MeV
450 MeV
90 MeV
cascade
A, mB/MeV/sr
Am


90 MeV
450 MeV
740 MeV
3170 MeV
b)
cascade
β
Am

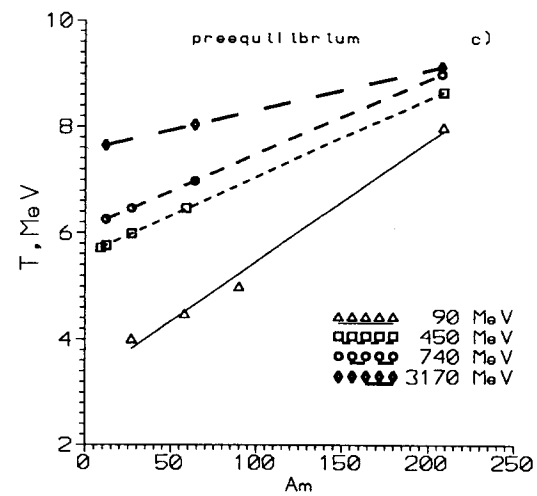
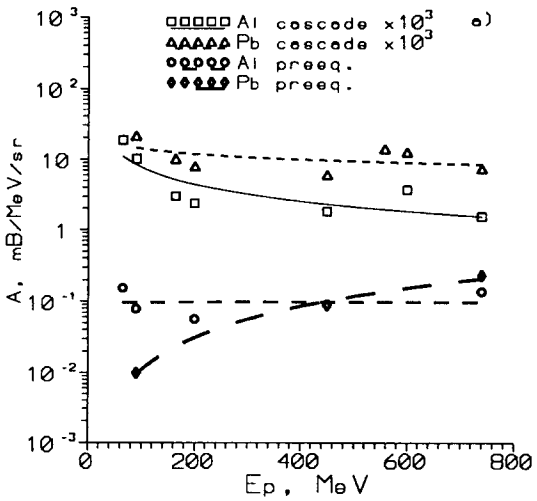
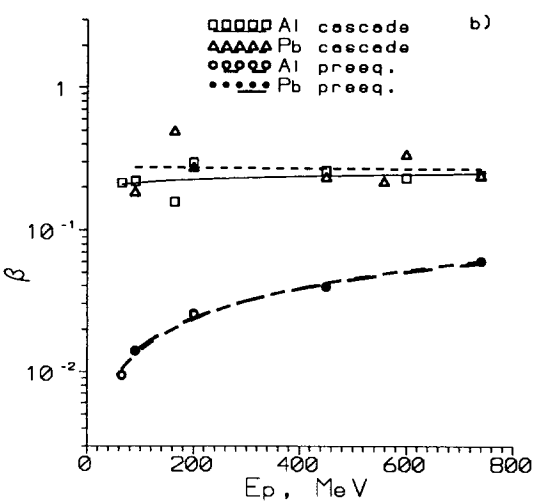

preequilibrium
c)
90 MeV
450 MeV
740 MeV
3170 MeV
T, MeV
Am

Fig. 3


Al cascade x10³
Pb cascade x10³
Al preeq.
Pb preeq.
a)
A, mB/MeV/sr
Ep, MeV


Al cascade
Pb cascade
Al preeq.
Pb preeq.
b)
β
Ep, MeV

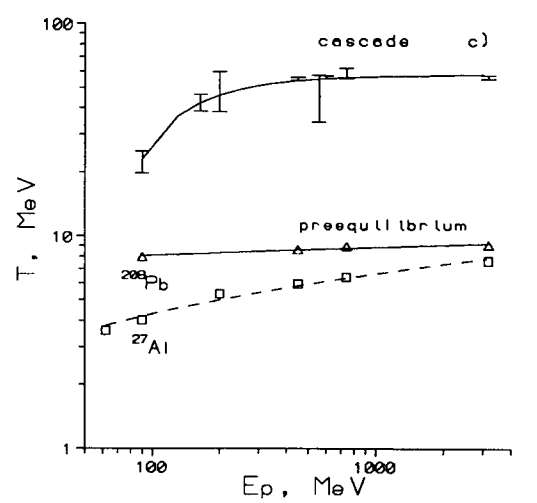

cascade
c)
preequilibrium
208Pb
27Al
T, MeV
Ep, MeV

Fig. 4

Fig. 5a

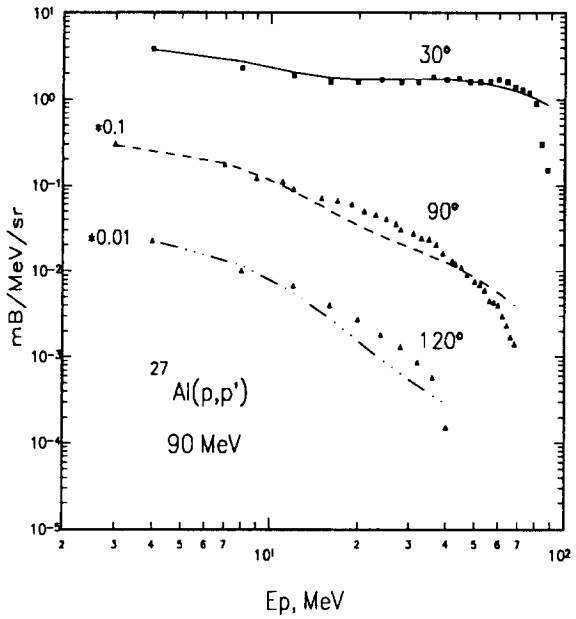


Fig. 5b

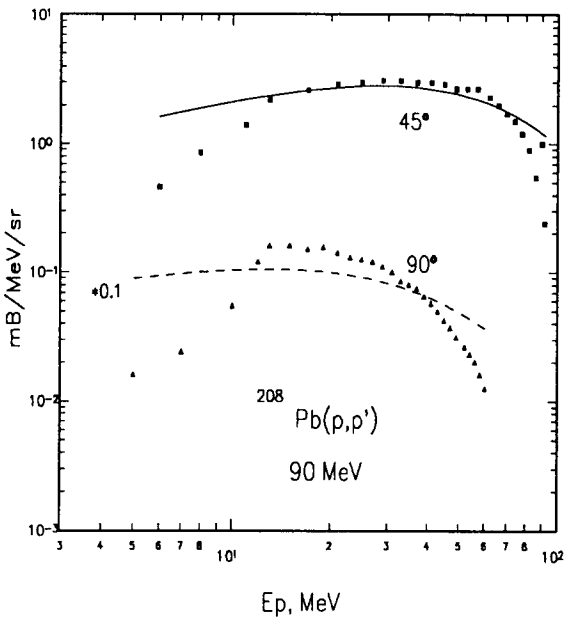


Fig. 6a

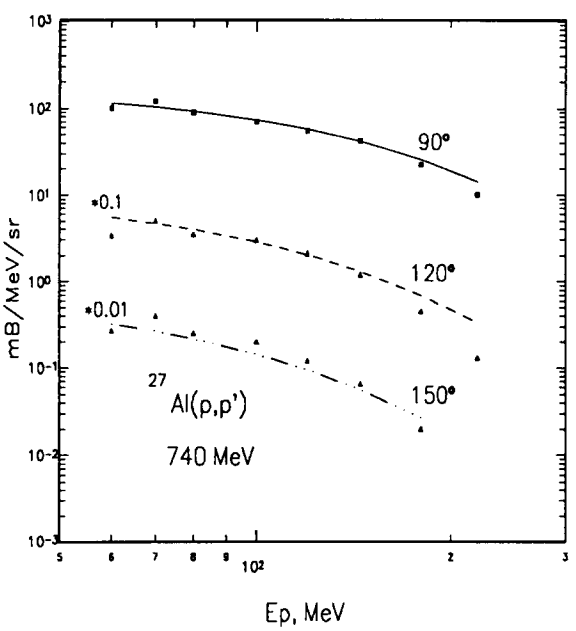


Fig. 6b

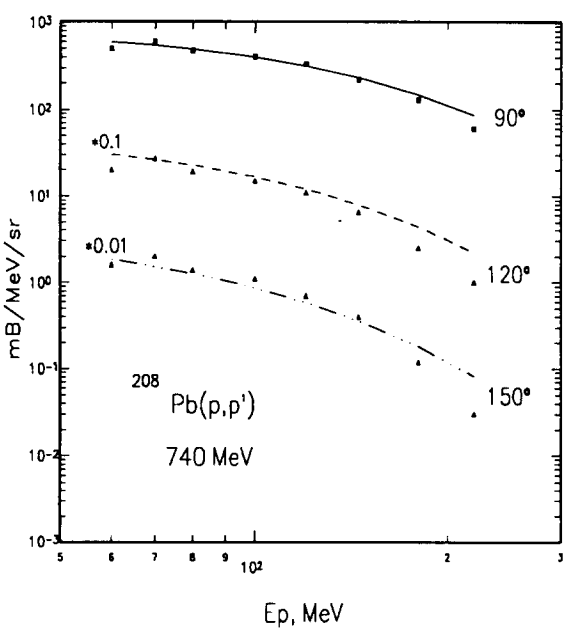


Fig. 7

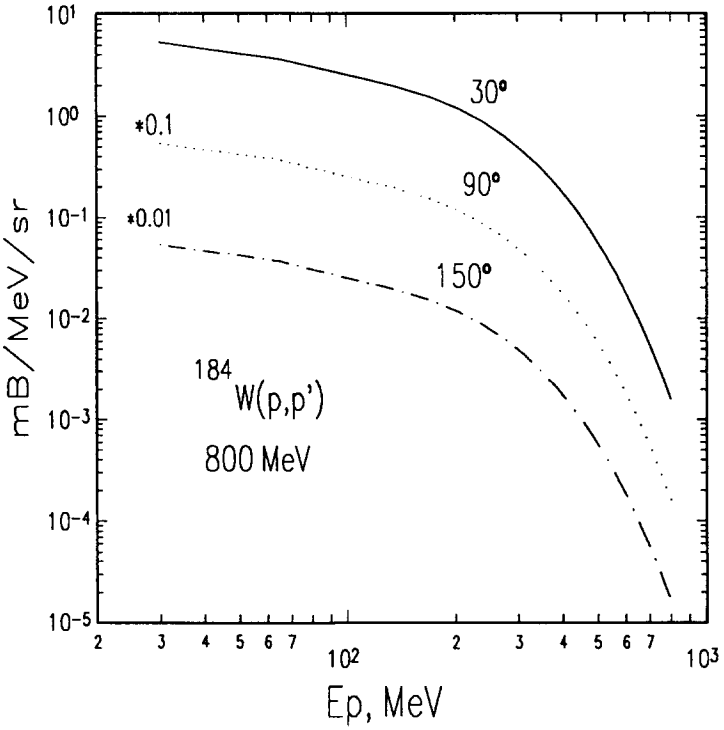

30°
*0.1
90°
*0.01
150°
184 W(p,p')
800 MeV
mB/MeV/sr
Ep, MeV

Fig. 8

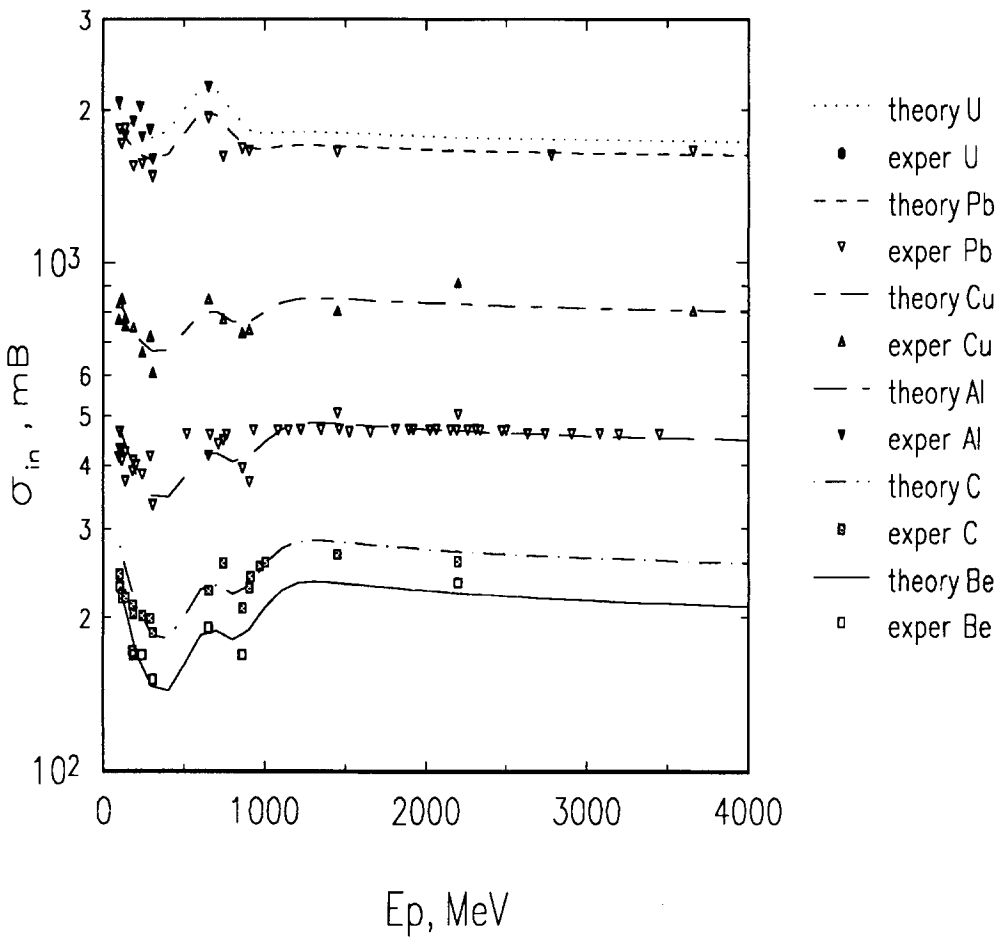

theory U
exper U
theory Pb
exper Pb
theory Cu
exper Cu
theory Al
exper Al
theory C
exper C
theory Be
exper Be
σ in , mB
Ep, MeV

Fig. 9a

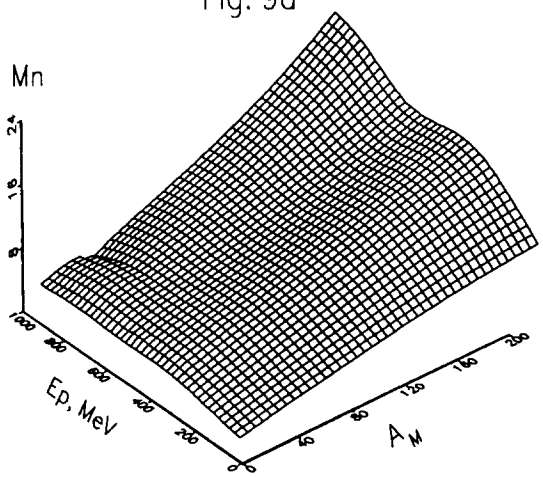


Fig. 10a

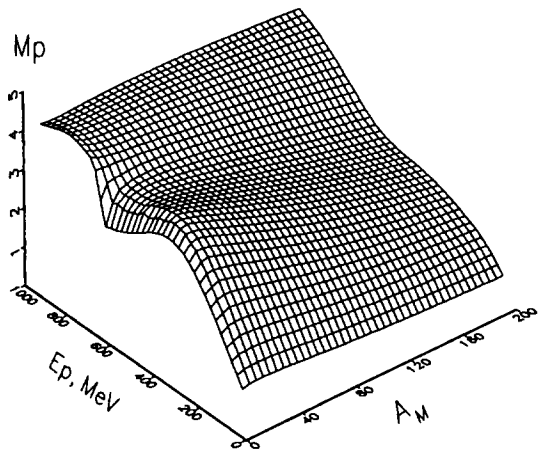


Fig. 9b

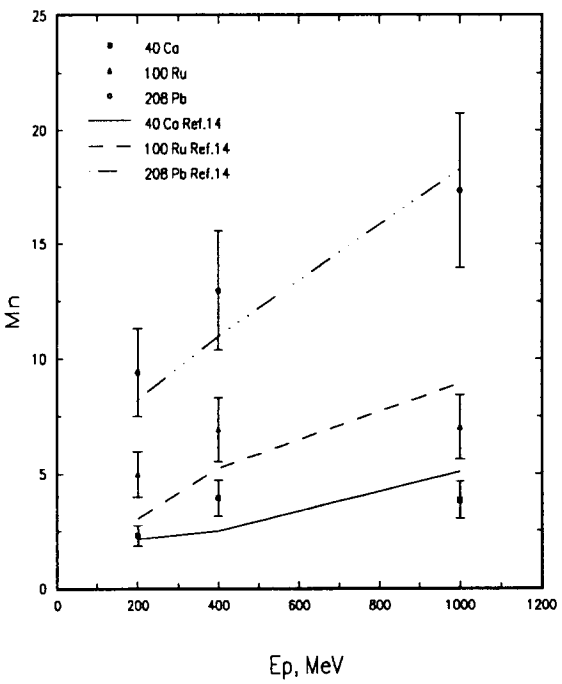


Fig. 10b

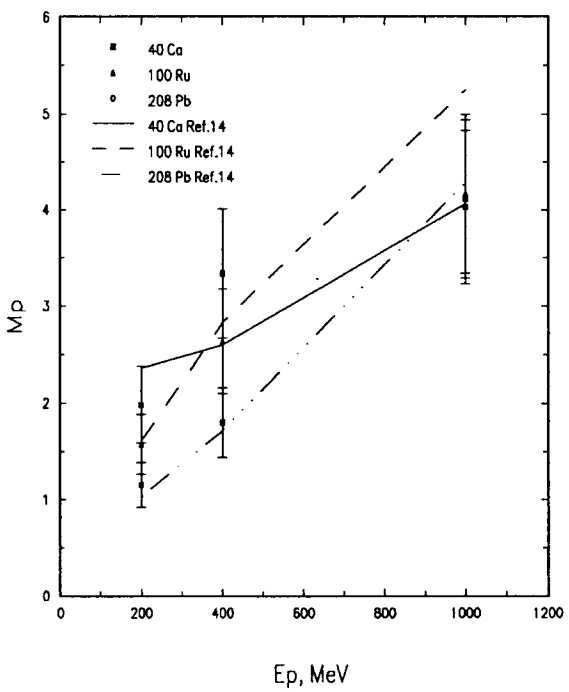


Fig. 11a

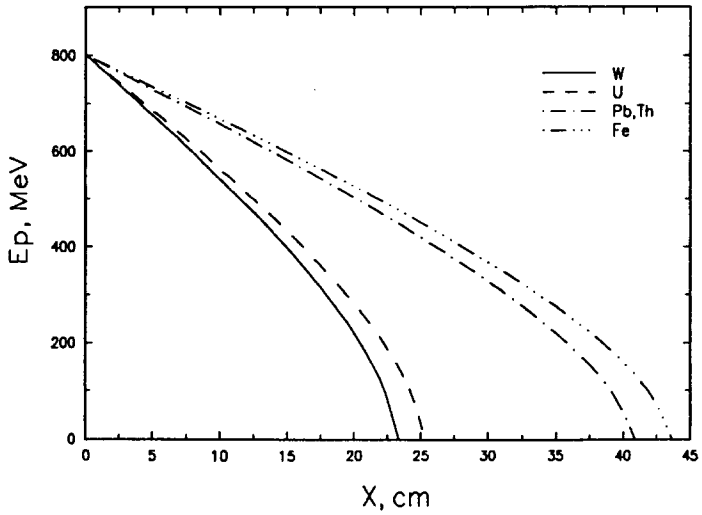


Fig. 11b

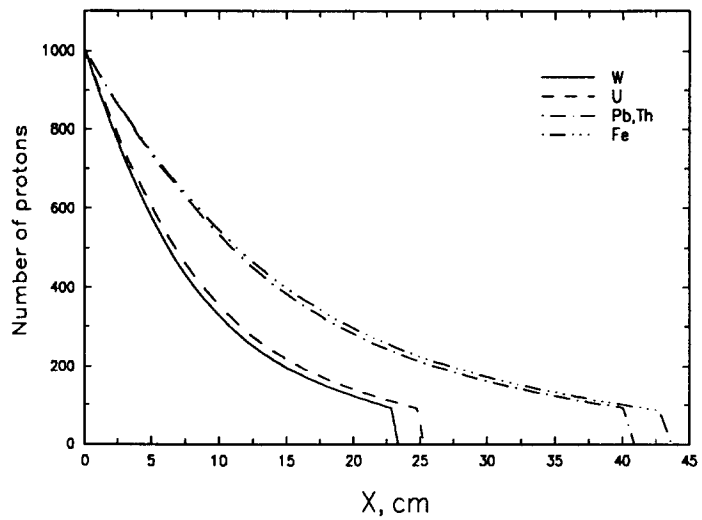


Fig. 11c