Comparison between Preequilibrium and Intranuclear Cascade Models at Intermediate Energies

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Abstract

The methods to obtain intermediate energy nuclear data are discussed. Results of calculations of proton and neutron integral and differential spectra using the preequilibrium hybrid model are compared with the intranuclear cascade model prediction for reactions induced by protons and neutrons with energies up to 100 MeV and with available experimental data. The difference between calculated and experimental data is more pronounced for the differential spectra at small angles, for integral spectra the difference is not so large. The necessity of taking into account the direct transitions to the low laying collective states and the possibility to improve the methods used are noted out.

1. Introduction

The prequilibrium models and intranuclear cascade models are still the most popular approaches which are used to obtain the differential cross-sections and excitation functions for nuclear reactions induced by intermediate energy particles. The development of both models during last decades allowed to describe a wide range of experimental characteristics of both equilibrium and nonequilibrium nuclear processes. The prequilibrium model has been traditionally aimed at study of reactions induced by particles with energies lower than 100 MeV, and intranuclear cascade model has been used at the higher energies.

According to [1] the differential cross-sections calculated with the help of exciton models and intranuclear cascade models at energies up to 100 MeV are quite different. However the conclusions of [1] need more accurate definition and discussion.

In the present work the cross-sections calculated using intranuclear cascade model (INC) and geometry dependent hybrid exciton model (GDH) are compared with experimental data. The goal of this comparison is to study the possibilities of models considered to reproduce the measured data at energies lower than 100 MeV, and to determine regularities in deviation of the calculated and experimental data.

In this work the differential cross-sections have been calculated for reactions induced by nucleons with energies from 6.0 to 62 MeV on medium mass and heavy nuclei.

2. Methods for Cross-Section Calculations.

2.1 Intranuclear Cascade Evaporation Model.

In the calculations the nucleus was divided into ten spherical zones with constant density. The radius of the most distant zone was estimated under condition that nucleon density in this zone is equal to 0.01 of that in the nucleus center. The potential distribution was determined according to the relation between Fermi energy in each zone and nucleon density.

For nucleon moving in the nonuniform potential, a partner and point of interaction were chosen using the method described in [2]. The effects of reflection and refraction of nucleon momentum at nucleus zone bounds were taken into account. Together with Pauli principle the restriction on angular momenta of nucleons was included in nucleon-nucleon interaction model [3]. This restriction on angular momenta of nucleons colliding in i-th zone has the following form

$$l < \mathbf{p}_{i+1} \mathbf{R}_i$$

where l is the orbital momentum of the nucleon with momentum $\mathbf{p}_i$ in the i-th zone, $\mathbf{p}_{i+1}$ is the momentum that the nucleon would have in the i+1 -th zone, R_i is the radius of the i-th zone.

The connection between $\mathbf{p}_i$ and $\mathbf{p}_{i+1}$ is expressed by the following relation of values of kinetic nucleon energy T_i and T_{i+1}

$$T_{i+1} = T_i - \varepsilon_i^F + \varepsilon_{i+1}^F$$

where ε_i^F is Fermi energy for i-th zone. If i-th zone has the maximum radius then $\varepsilon_{i+1}^F = -Q$, where Q is the nucleon binding energy.

The cutoff energy presenting the minimal energy of emitted nucleon was considered equal to zero for neutrons. The penetration of protons through Coulomb barrier was taken into account.

The nucleon binding energies were calculated using the Nuclide Mass Table (1988) [4] and were used in simulation of the intranuclear cascade processes.

The precompound effects described via exciton models have not been considered.

Numerical calculations have been carried out using the DISCA2 code [5].

2.2 Geometry Dependent Hybrid Exciton Model

Calculation of nucleon spectra was carried out taking into account multiple pre-compound emission according to [6]. The exciton state density was calculated using Ericson formula taking into account Pauli principle and pairing effects in level density. Nucleon-nucleon interaction cross-sections with the correction to the Pauli principle were used to calculate the intranuclear transition rates (λ_+). Normalization coefficient for the calculation of λ_+ value was taken to be equal to unity.

The description of precompound angular distributions was carried out in three dimensional geometry taking into account the refraction of nucleon wave in entrance channel [7]. No systematics for description of the angular distributions have been used in calculations.

Numerical calculations have been carried out using the modified ALICE code [8].

3. Comparison of Calculated and Experimental Data

Figs. 1-8 represent the calculated spectra for protons emitted at angles from 12° to 135° for ^{54}Fe and ^{209}Bi irradiated by 62-MeV protons. The angle integrated proton spectra for these nuclei are shown in Figs. 9 and 10. The experimental data are cited from [9]. Both model calculate equilibrium and nonequilibrium parts of spectra and sum of them is represented on figures as solid line for INC model and long dashed - for GDH.

The deviation of spectra calculated via intranuclear cascade evaporation model for experimental data at angles 30° and 60° (figs. 6,7) refers to the overestimation of the calculated evaporation spectrum. At the same time both models underestimate spectra at small angles (Fig. 1, 5). Narrow peaks in high energy part of spectra are connected with excitation of low laying collective states and giant resonances in inelastic scattering. The total contribution of direct excitation of this states in integral spectra is about 100 mb for 62-MeV protons scattered on Lead nuclei.

It should be noted generally, that the calculation of the hard part of the nucleon spectra for 62-MeV protons on the basis of different approaches gives the close results. Such agreement of the calculated data is observed also in comparison of spectra obtained for reactions taking place at lower energies.

The calculated spectra are shown in Fig.11 for neutrons emitted with energy equal to 19 MeV from ^{93}Nb nucleus irradiated by 25.7-MeV neutrons. The measured data are taken from [14]. Both calculations underestimate experimental point at 25°.

Figs.12,13 present calculated neutron spectra for p+^{208}Pb reaction at incident proton energy equal to 25.5 MeV in comparison with experimental data for two angles. The experimental data was taken from [10]. We can see that for charge exchange reaction like (p,n) the contribution of direct processes is rather small. INC model gives better description for backward angles in hard part of spectra.

The angle integrated proton spectra for neutron induced reaction on ^{54}Fe and ^{60}Ni nuclei for 14.8 MeV incident energy calculated via different approaches are shown in figs.14 and 15 together with experimental data [11]. Low energy part of spectra connected with equilibrium processes is not reproduced in INC model.

Figs.16, 17 and 18 illustrate the calculated neutron differential cross-section for reaction taking place in interaction of 25.6, 14.1 and 5.97-MeV neutrons with ^{209}Bi in comparison with experimental data. The measured spectrum is taken from [12,13,14]. Contribution of direct processes in inelastic scattering was calculated by ECIS code [15] for ^{208}Pb nucleus and then smoothed with experimental resolution width. Important input parameters for this calculations was taken from the description of the data received in experiments on proton inelastic scattering performed with high resolution for ^{208}Pb. Nucleus ^{209}Bi we can consider in frame of model of weak coupling of odd proton with even-even core. All details of this calculation was published in [16]. We can see that all peaks in high energy part of neutron spectra are connected with direct excitation of low laying collective states of ^{209}Bi. If projectile energy is increased the resolution became worse and all peaks are smoothed out. In the case of proton inelastic scattering we have good resolution even for 62-MeV, to resolve groups of collective levels.

4. Conclusion

Comparison of experimental data and calculated differential cross-sections (the examples are shown on Figs.1-18) performed allows to conclude:

- intranuclear cascade and hybrid exciton models can reproduce the parts of experimental spectra that are not connected with collective states of formed nuclei for reactions induced by nucleons with energy above a few MeV;
- the possibility of intranuclear cascade model to describe the experimental data at energies lower than 50 MeV is connected with more accurate definition of the model algorithm;
- the application of models employed to calculate the nonequilibrium particle spectra gives the good agreement and close results.
- the improvement of the methods considered is connected with the evaluation of the validity of assumptions used and with account of the most important nuclear features.

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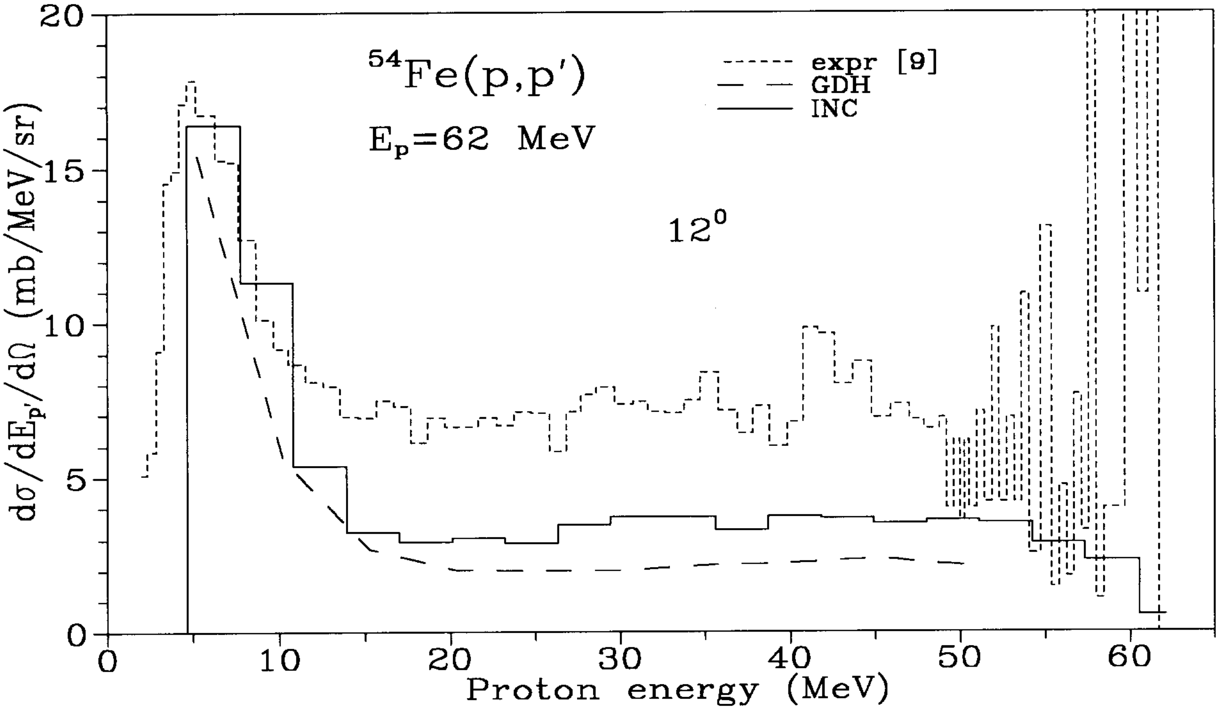

Fig.1 The proton double differential cross-sections at angle 12° for p+ ^{54}Fe reaction at the incident energy equal to 62 MeV calculated using intranuclear cascade evaporation model (solid histogram) and geometry dependent hybrid exciton model (long dashed histogram) are compared with experimental data (short dashed histogram).

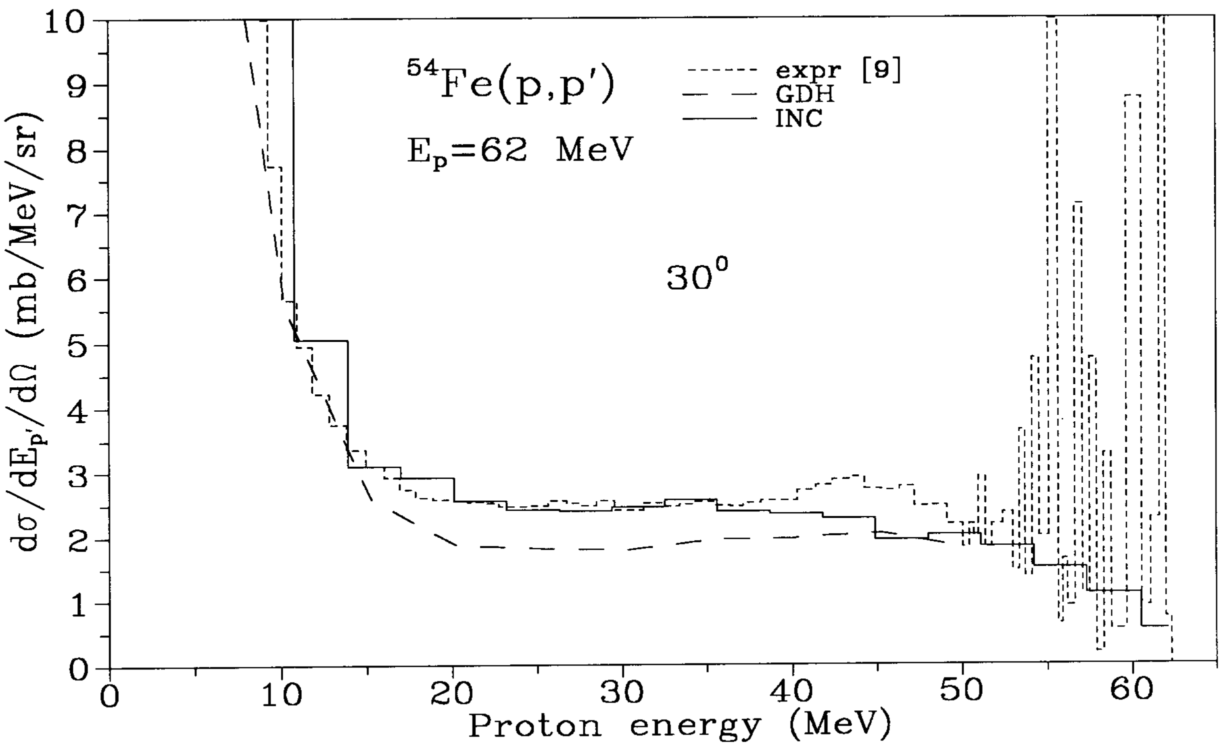

Fig.2 The same as on fig.1, but for angle 30°.

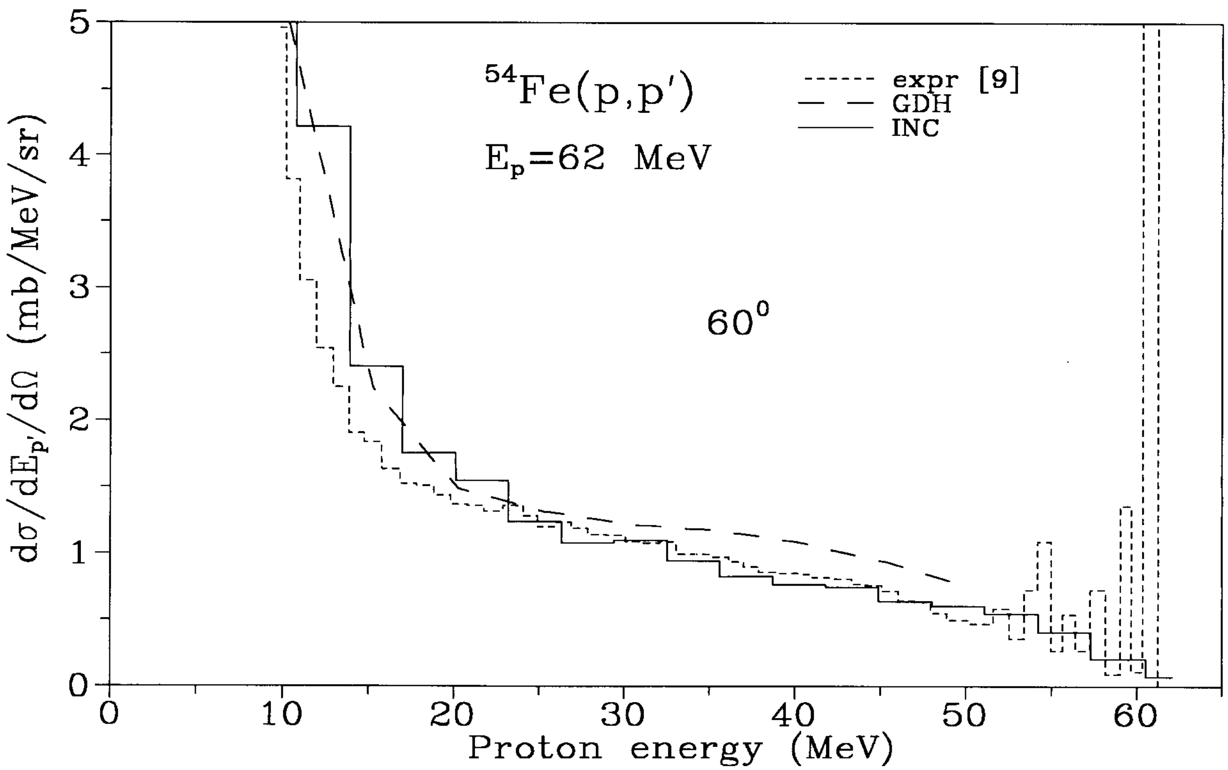

Fig.3 The same as on fig.1, but for angle 60°.

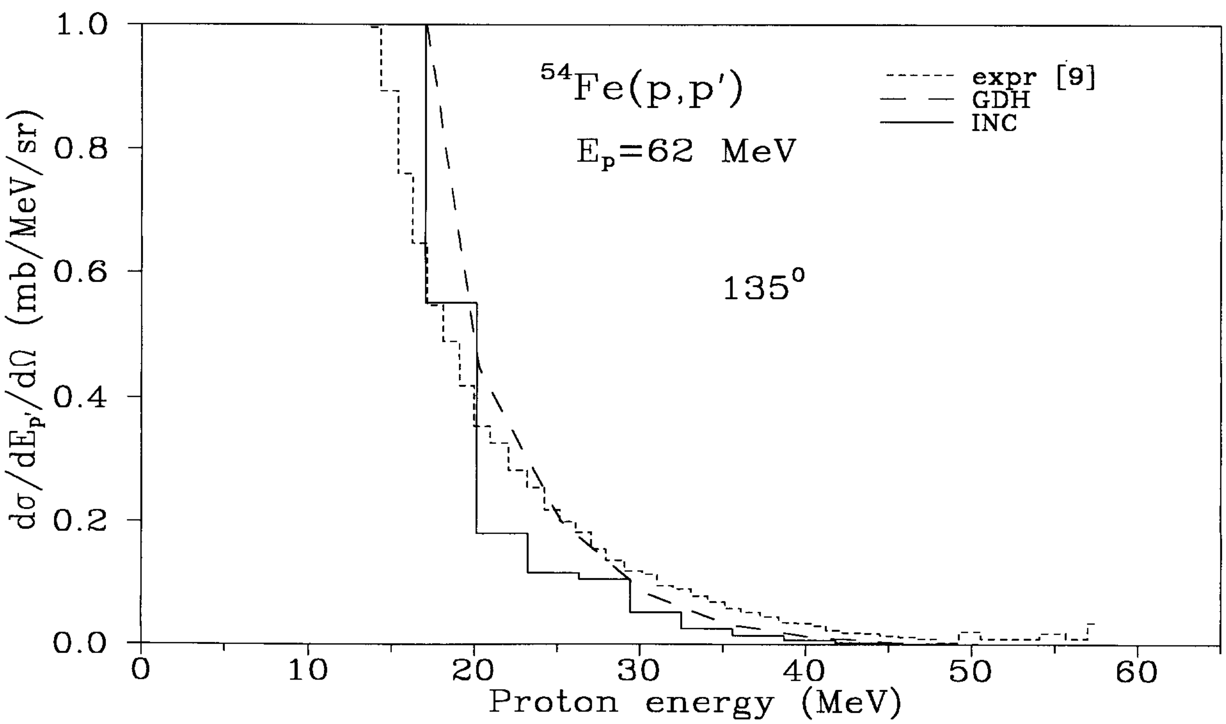

Fig.4 The same as on fig.1, but for angle 135°.

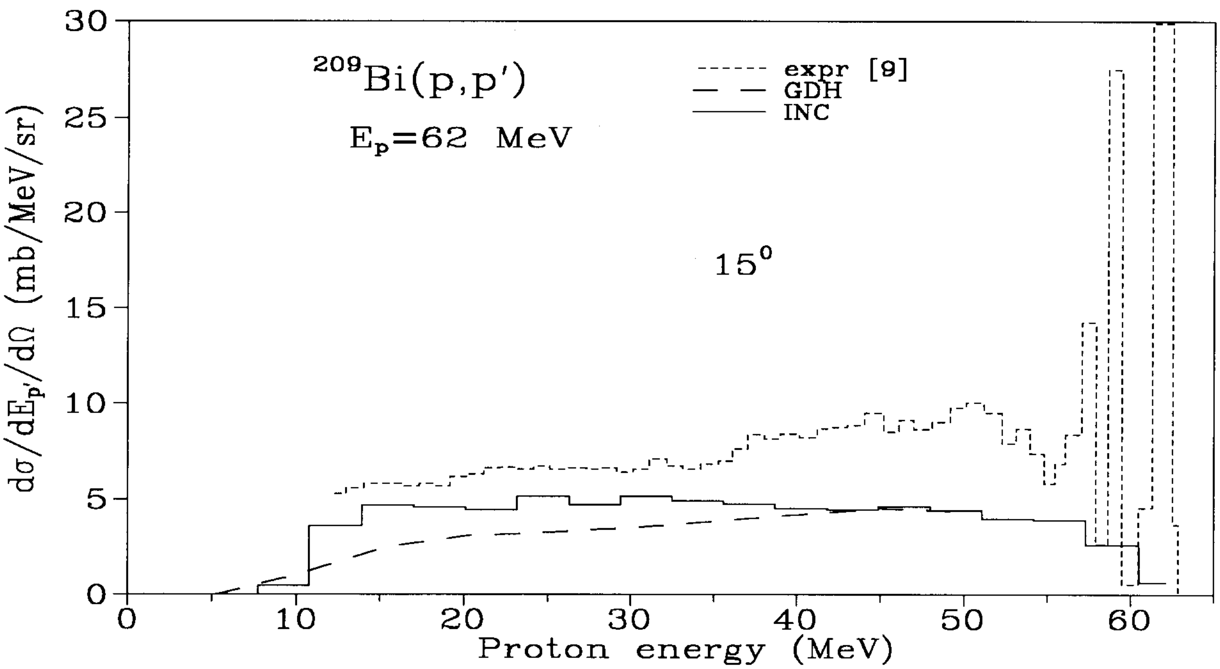

Fig.5 The proton double differential cross-sections at angle 15° for p+ ^{209}Bi reaction at the incident energy equal to 62 MeV calculated using intranuclear cascade evaporation model (solid histogram) and geometry dependent hybrid exciton model (long dashed histogram) are compared with experimental data (short dashed histogram).

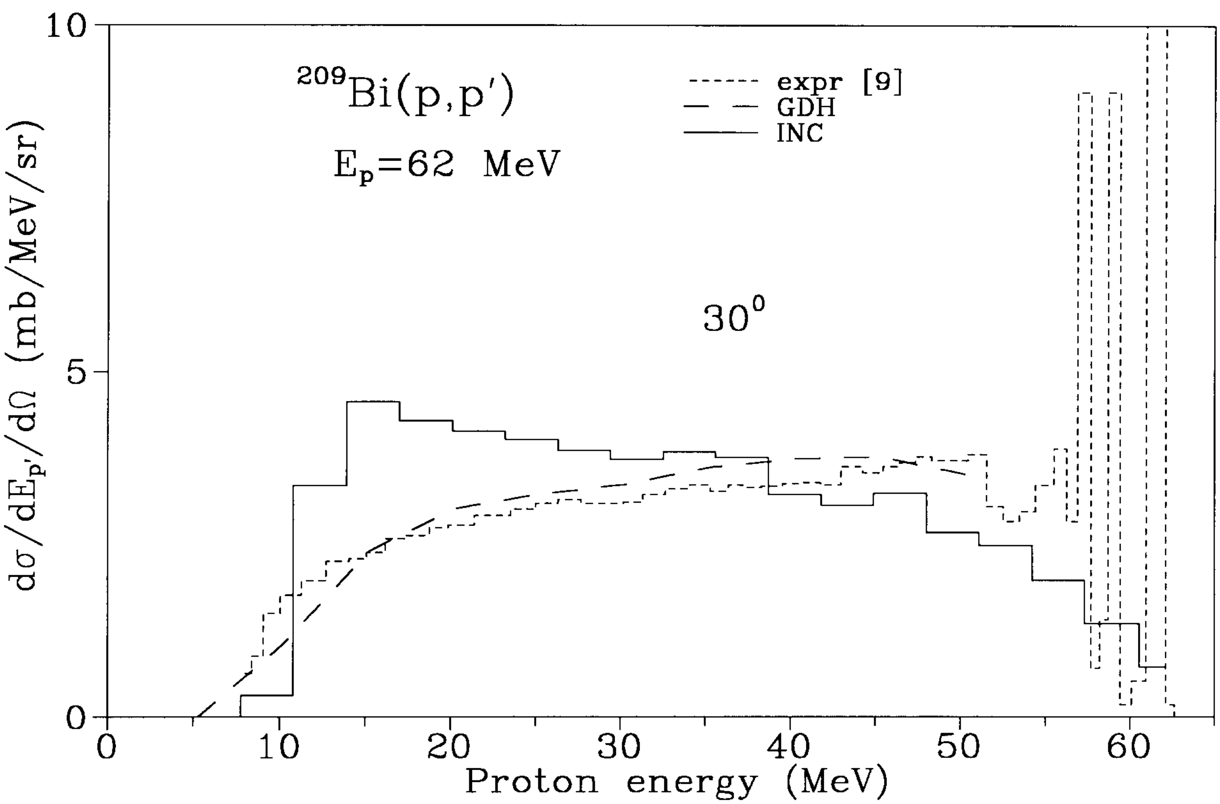

Fig.6 The same as on fig.5, but for angle 30°.

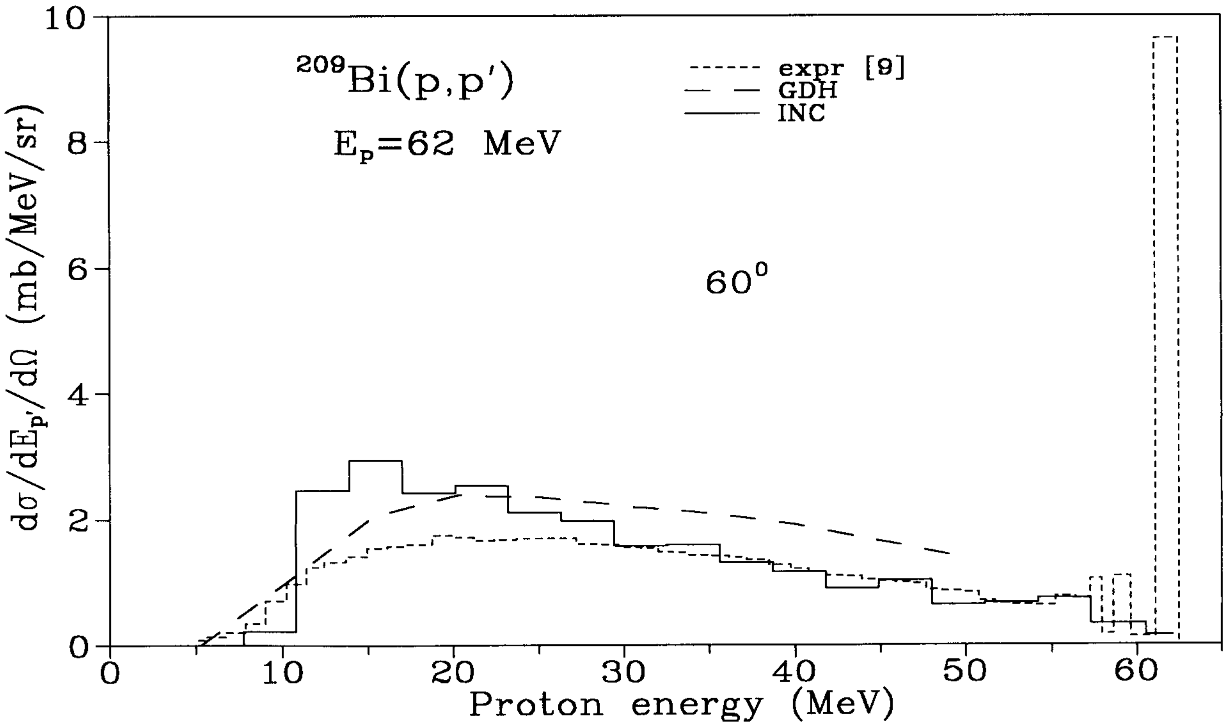

Fig.7 The same as on fig.5, but for angle 60°.

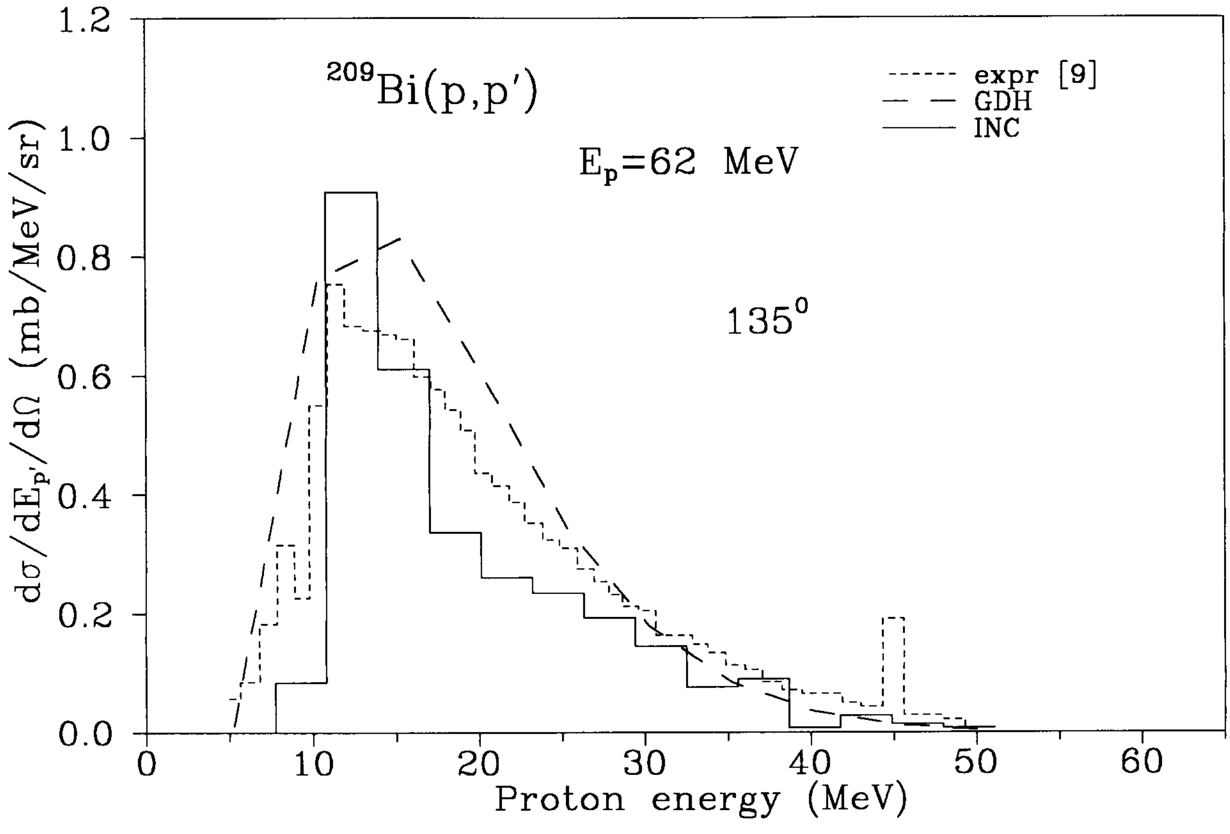

Fig.8 The same as on fig.5, but for an.135°.

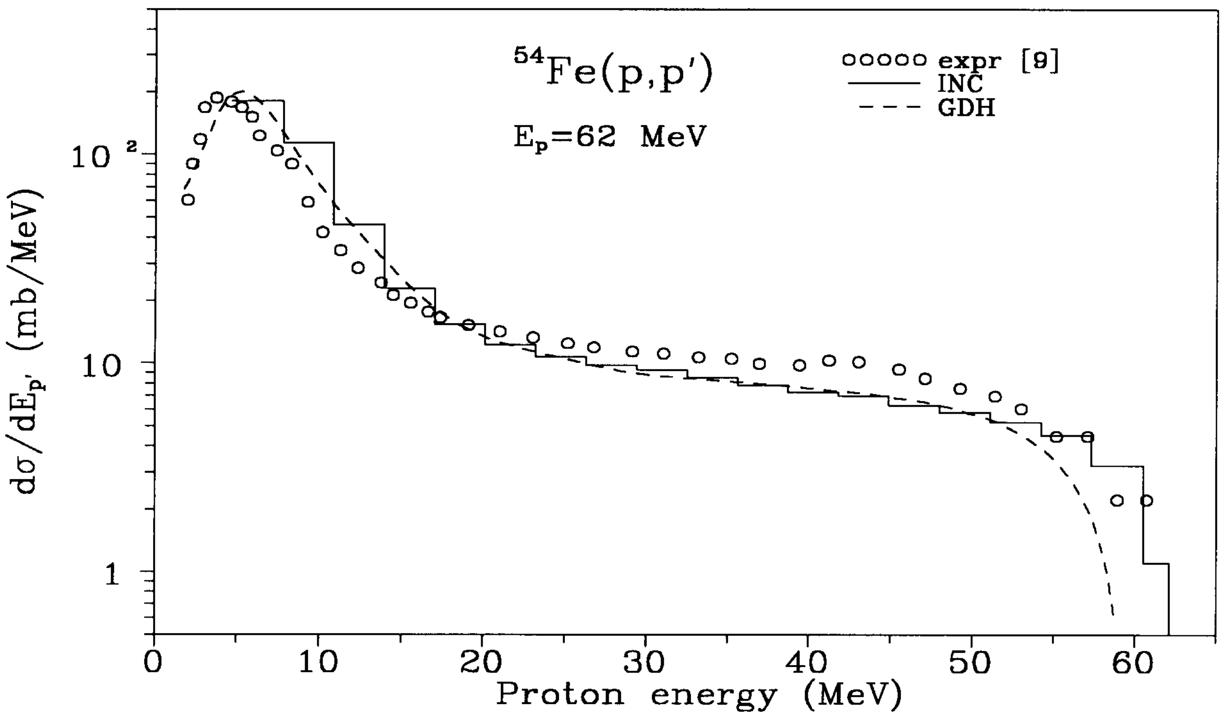

Fig.9 The angle integrated proton spectra for ^{54}Fe(p,p') reaction at the primary proton energy equal to 62 MeV calculated via different approaches are compared with experimental data (open circle). The other symbols are the same as on Fig.1.

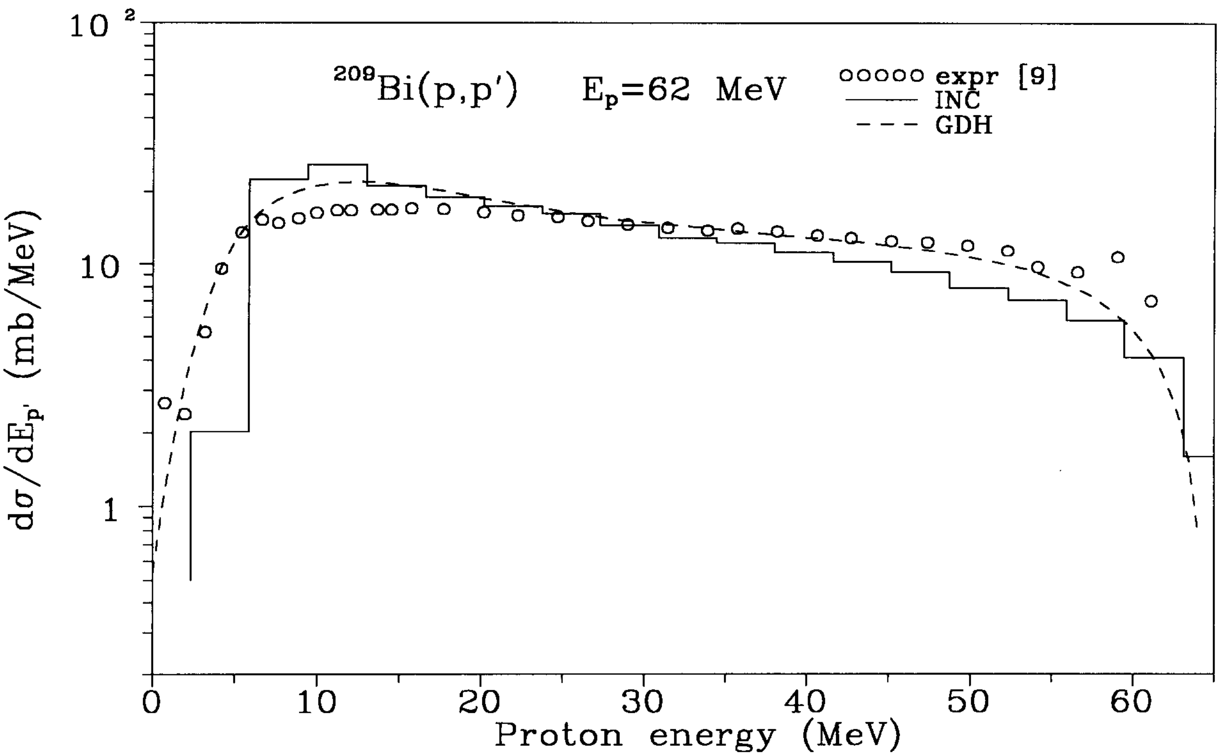

Fig.10 The same as on fig.9, but for ^{209}Bi(p,p') reaction.

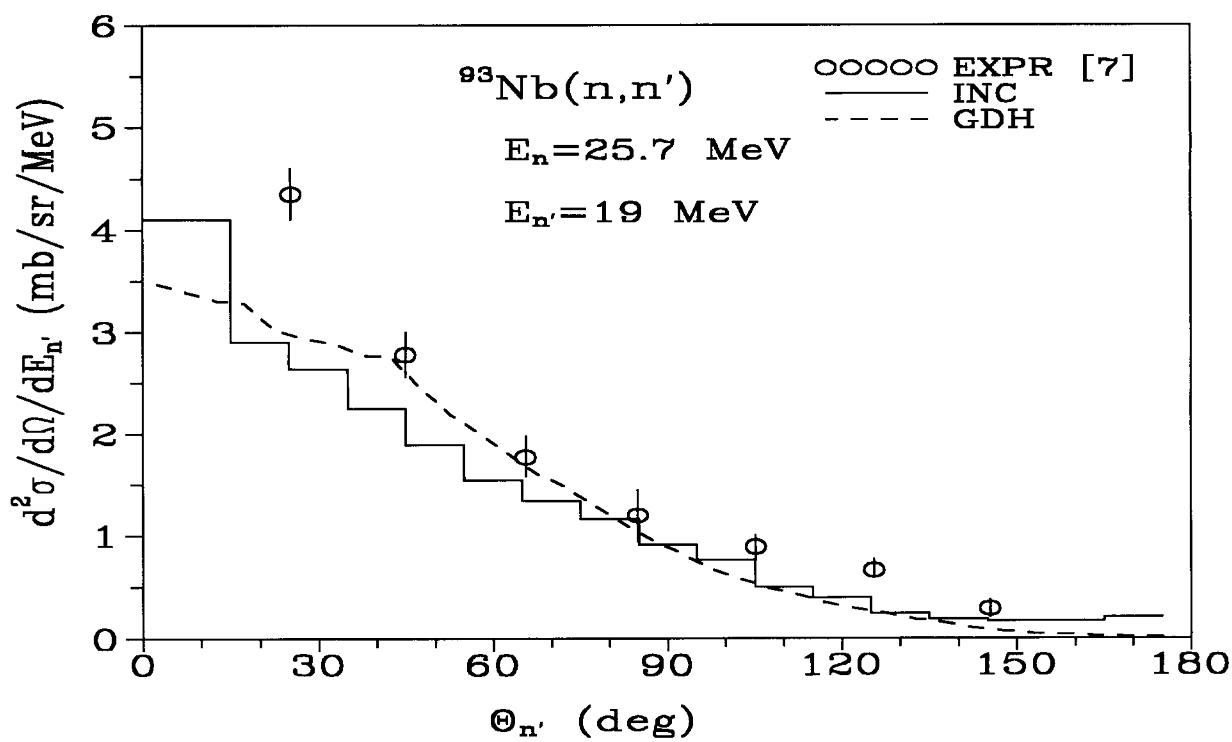

Fig.11 The calculated and experimental double differential cross-sections for neutrons emitted with energy equal to 19 MeV in reaction taking place in irradiation of ^{93}Nb by 25.7-MeV neutrons. The symbols are the same as on Fig.9.

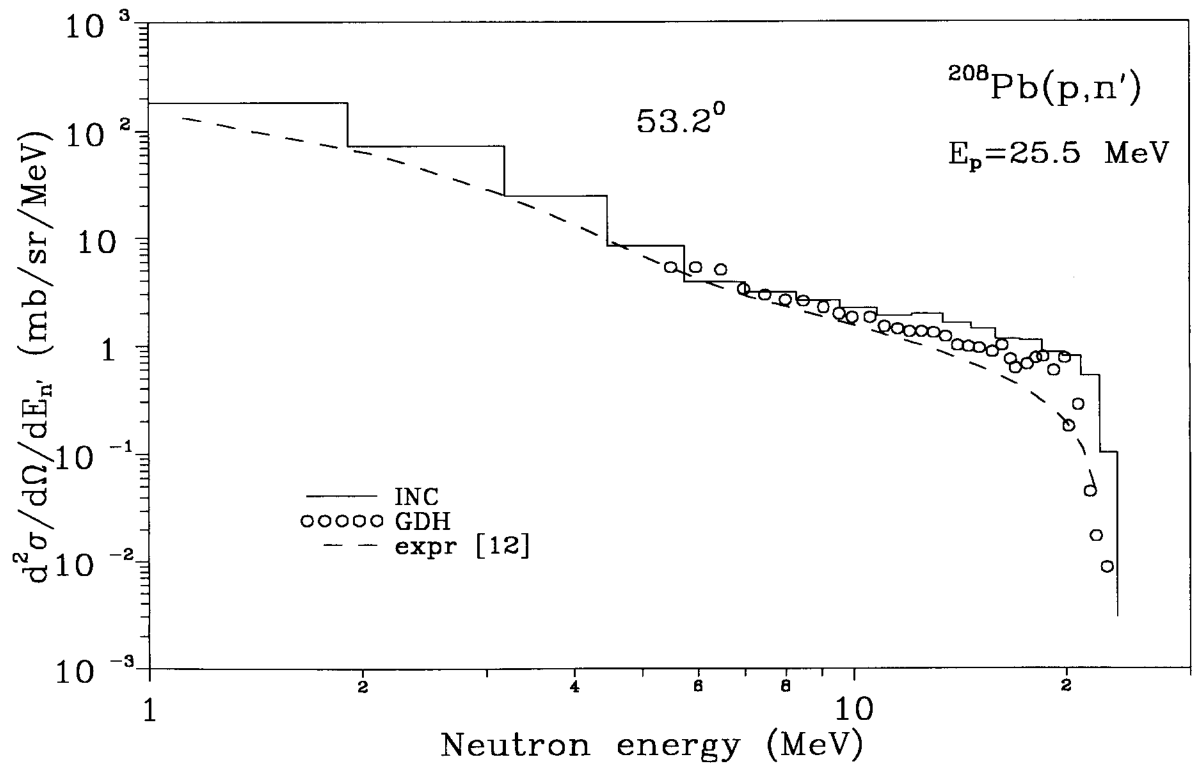

Fig. 12 Experimental and calculated double differential neutron cross section at 53.2^0 for 25.5-MeV proton incidence on Pb.

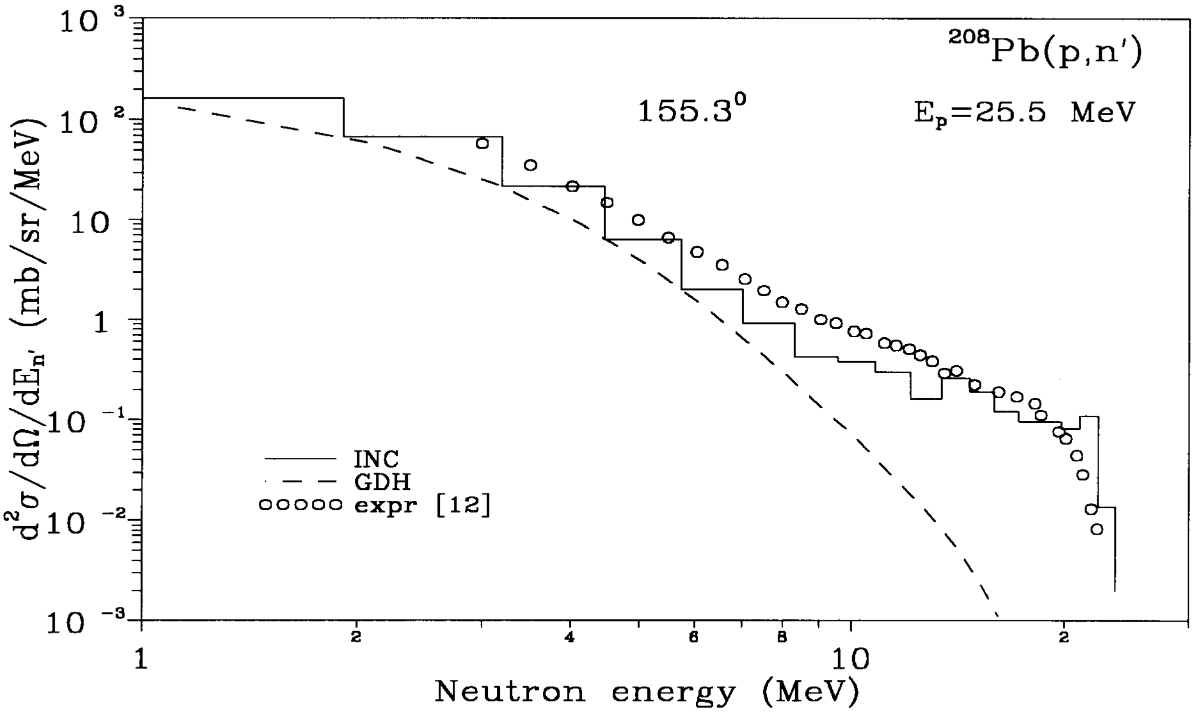

Fig. 13.Experimental and calculated double differential neutron cross section at 155.3^{0} for 25.5-MeV proton incidence on Pb.

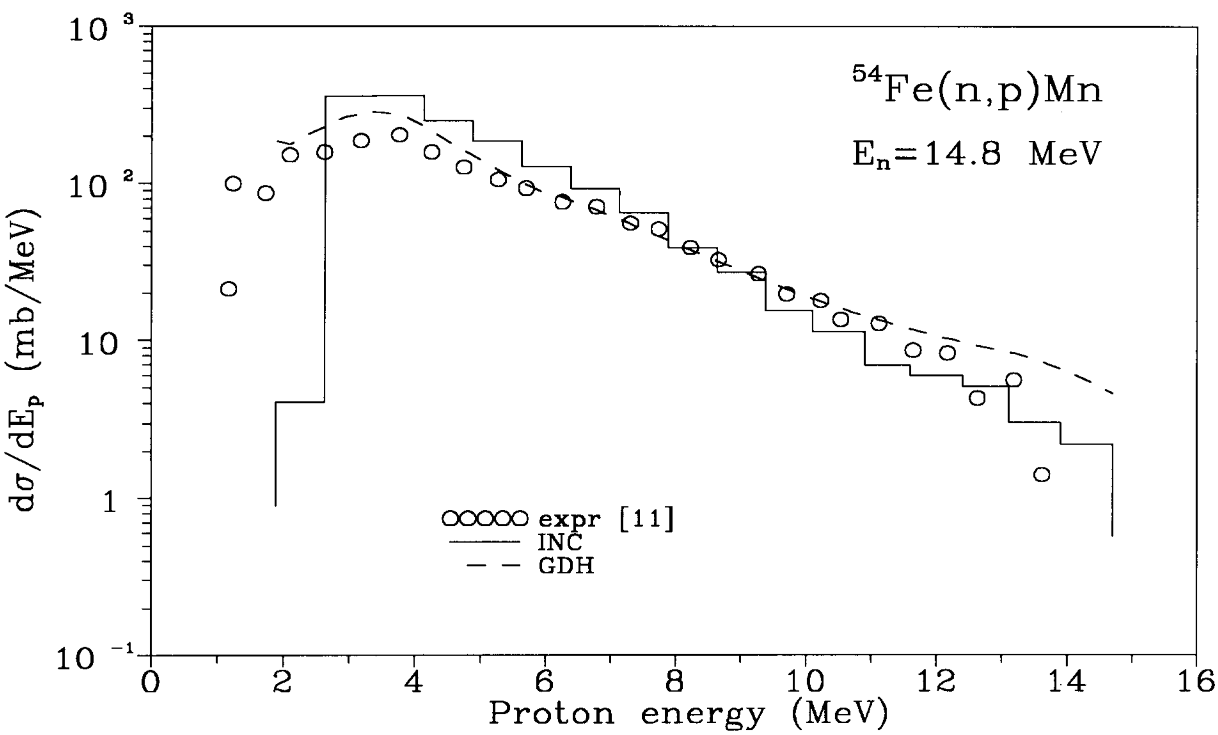

Fig.14 The angle integrated proton spectra for $^{54}Fe(n,p)Mn$ reaction at the primary neutron energy equal to 14.8 MeV calculated via different approaches are compared with experimental data. The symbols are the same as in Fig.9.

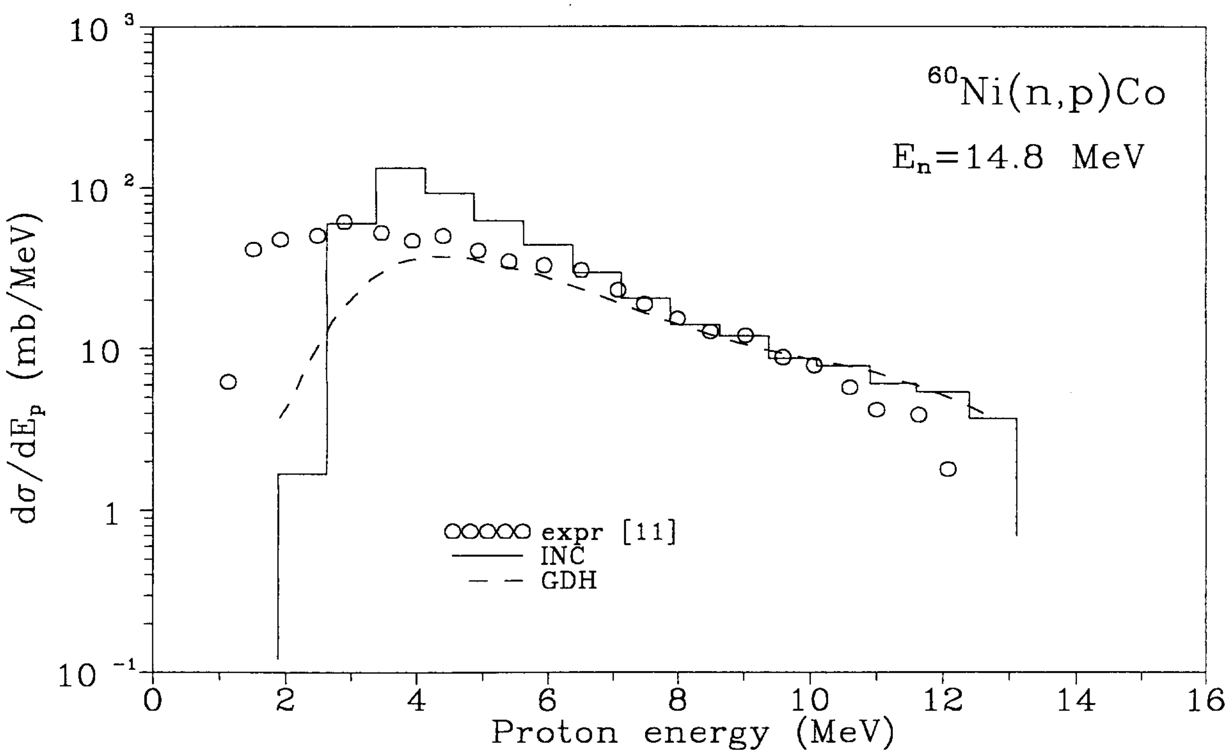

Fig.15 The same as on Fig.12, but for ^{60}Ni(n,p)Co reaction.

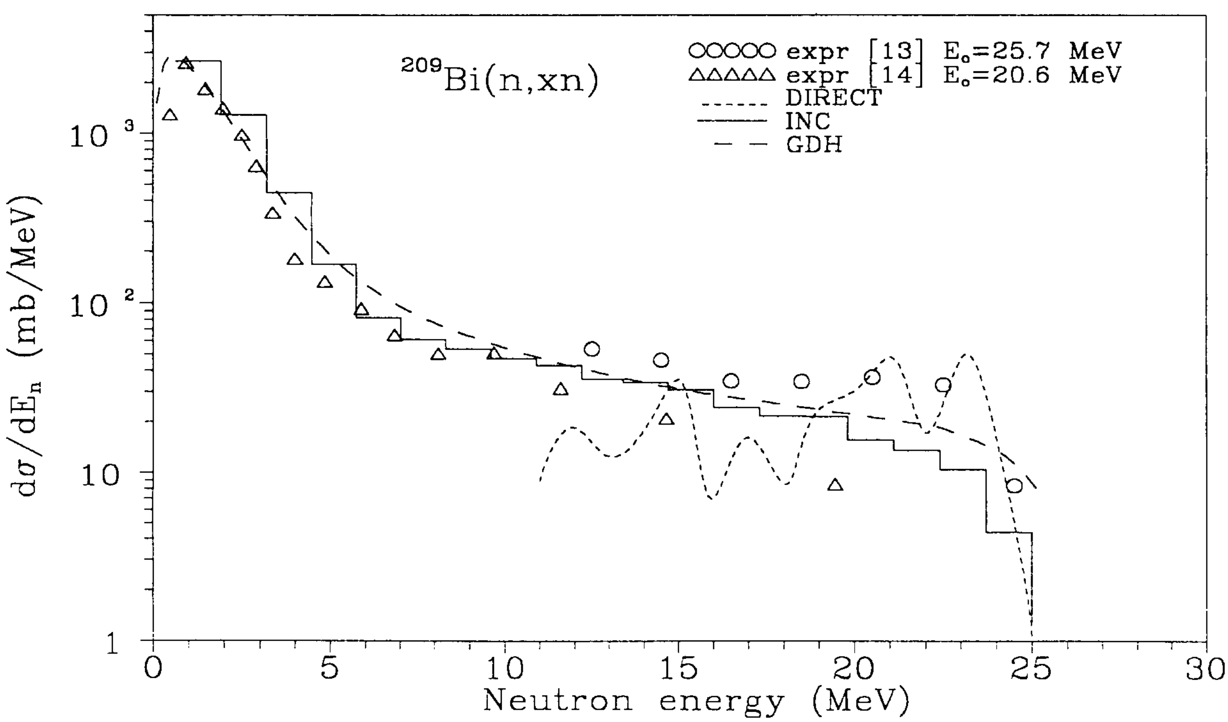

Fig.16. The angle integrated neutron spectra for ^{209}Bi(n,n') reaction at the primary neutron energy equal to 25.6 MeV calculated via different approaches.

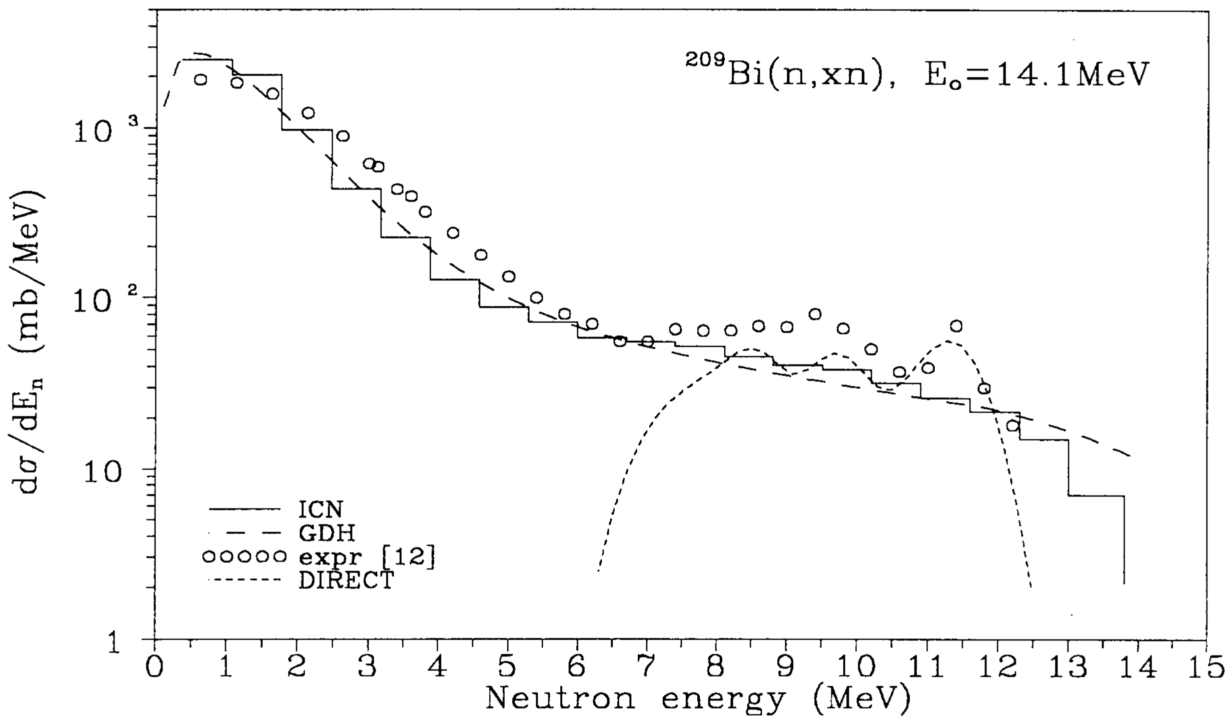

Fig.17. The angle integrated neutron spectra for ^{209}Bi(n,n') reaction at the primary neutron energy equal to 14.1 MeV calculated via different approaches.

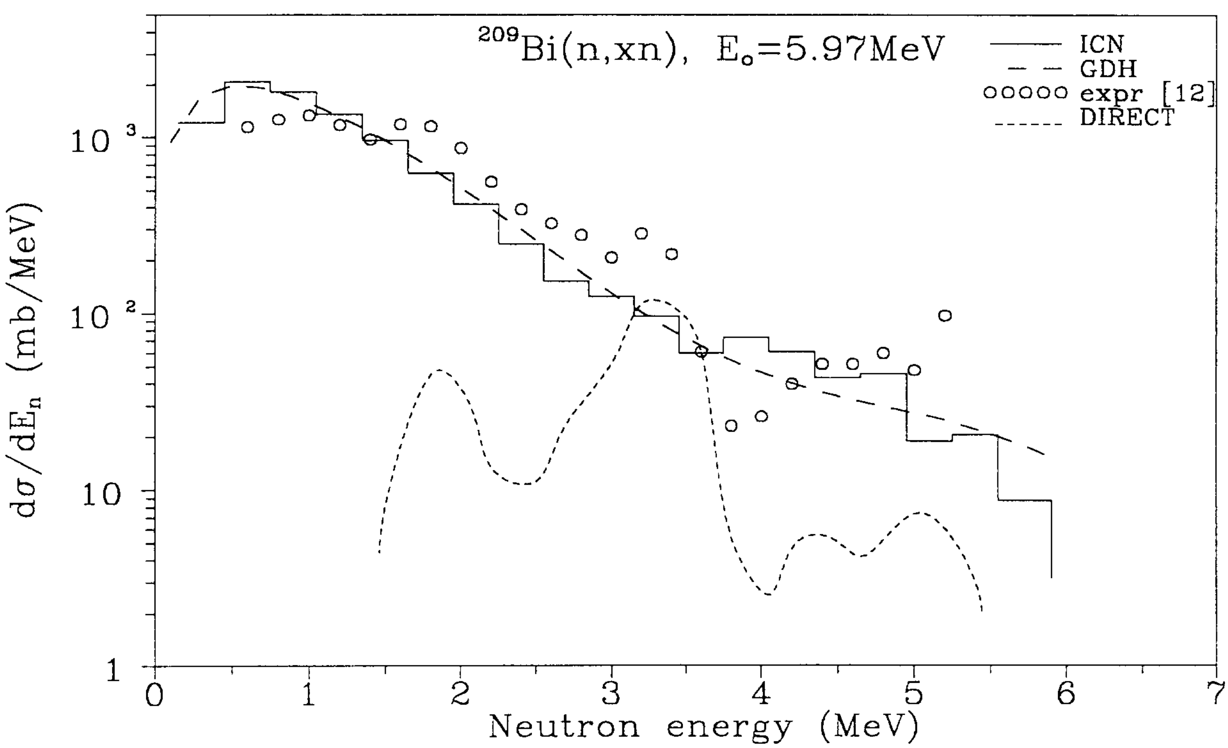

Fig.18. The angle integrated neutron spectra for ^{209}Bi(n,n') reaction at the primary neutron energy equal to 5.97 MeV calculated via different approaches.