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A.A.Sibirtsev

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The experimental data on proton-nucleus and pion-nucleus collision obtained at LAMPF and SATURN are analysed in order to establish the reaction mechanisms. The pion induced reactions are well reproduced by the one-step approach. We found that the η-energy spectra produced in $\pi+A$ collisions directly reflect the nucleus single-nucleon momentum density. The production of η-mesons in p+A collisions is not described reasonably by using both one- and two-step models. We discuss the reasons of the discrepancies between the experimental and model results. The reabsorption of η-mesons in nuclear medium is studied in order to analyse the difference between the existing approaches on this process.

Fig. - 7, ref. - 23

1 Introduction

The SATURNE results on eta-meson production in $p + d \rightarrow \eta + {}^3He$ reaction has attracted much regular interest. The most surprising finding in the experiment [1] was an enormous high η-production cross section in the same order of magnitude as those for π^0-production. The result can be considered as direct evidence for the three-body mechanism [2, 3]. However, the strong and perpetual theoretical attempts to reproduce the experimental data seem still failure.

Quite similar situation stands for inclusive η-production, that involves two-body mechanism, in proton-nucleus collisions at bombarding energies below the free NN threshold. The resent results on eta production cross section as well as the A-dependence and energy spectra are not reproduced by means of the standard theoretical models considered subthreshold particle production [4]. It seems more unexpected because the involved models successfully describe a lot of experimental data on subthreshold π, K^+-mesons and antiproton production in proton-nucleus and heavy ion collisions [5, 6, 7, 8].

Particle production in proton-nucleus collision at bombarding energies below the threshold for the reaction on free nucleon is of considerable interest. The deficiency of incident proton energy to produce the particle on free nucleon forces one to attract the ideas on collective interaction involved several bound nucleons. Except of the few-body mechanism the particle can be produced directly due to the internal nuclear motion. At collision energies far below the NN-threshold the account for the standard Fermi-gas groundstate momentum distribution is not enough to create required energy and the extreme momentum components is necessary. Thus the study of the subthreshold particle production can get important information about the nuclear structure at very short distances.

The model suggested for the subthreshold particle production took account for both few-body mechanism and high momentum component of the nuclear wave function. We supply the detail information for production dynamics in order to make precise calculation on it. Thus we sure about the reaction mechanism. Nevertheless the more complicated problem is the rescattering of produced η-mesons in nuclear media.

The η-meson reabsorption in nuclear environment is exceedingly strong. According to isospin the η-nucleon system can couple to the N^* resonances only, whereas the π-nucleon system couples both to the Δ and N^* resonances. Even more the $N^*(1535)$ and the $N^*(1710)P_{11}$ resonances are the only baryonic states strongly coupled to the η-nucleon channel. The study on the $\pi^- + p \rightarrow \eta + n$ angular distribution by Feltesse et al. [10] has shown the dominant role of the $N^*(1535)$ resonance at the threshold. Thus eta-meson production allows to study the properties of N^* resonances within the nuclear medium. Because the $N^*(1440)P_{11}$ Roper resonance lies below the eta-nucleon threshold, subthreshold η-production in proton-nucleus collisions seems to be sensitive to this resonance reflecting the coherent interaction of baryons inside the nucleus. Cassing et al [9] found that eta-rescattering inside the nucleus trends to the decreasing of the observed cross section by a factor of ten due to the excitation of the $N^*(1535)$ resonance. Obviously the secondary interactions of eta's with nuclear nucleon significantly distort the original spectra. As the result the analysis of η-production on nuclear target is both complicated and inadequate.

The study of η-meson production proton-nucleus collisions is proposed for Celsius [11] and Cosy [12]. Before the detailed experimental study we are to analyse the experimental data already measured by means of the production models and to understand the contribution of the different reaction mechanisms to the η-production process.

In this paper we study the one-body and two-body reaction mechanisms in order to analyze subthreshold η-production in pion- and proton-nucleus collision. We use the folding model for primary and secondary production processes that was adequate in the description of the subthreshold phenomena.

2. Production mechanisms

2.1 Direct η-meson production

We consider the following interaction picture for subthreshold η-production in hadron-nucleus collision.

The η-meson is produced in the first collision of the incident hadron with a nuclear nucleon due to the internal nuclear motion

$$p + N \rightarrow N + N + \eta \quad (1)$$

$$\pi + N \rightarrow N + \eta \quad (2)$$

The standard way to describe the internal motion of the nucleons is to use the Fermi-gas groundstate momentum distribution, which provides a maximum internal momentum of about 250 MeV/c. We use a uniform distribution of the nucleon momenta inside a momentum sphere with radius p_F

$$p_F = \hbar \sqrt[3]{\frac{3\pi^2 \langle\rho\rangle}{2}} \quad (3)$$

where $\langle\rho\rangle$ is average nuclear density.

In order to analyze the particle production at bombarding energies far below the hN-threshold it is necessary to take into account the high momentum component of the nuclear wave function.

We use the double-gaussian function suggested by Geaga et al. [13]

$$\Phi(q) = \frac{\exp\left(-q^2/2\alpha^2\right)}{\alpha^3} + \gamma\, \frac{\exp\left(-q^2/2\beta^2\right)}{\beta^3} \quad (4)$$

The distribution is normalized to unity. The first term describes the Fermi-gas momentum distribution with $\alpha = 115$ MeV/c whereas the second term represents the high-momentum components with $\beta = 230$ MeV/c and a relative contribution $\gamma = 0.06$ for a carbon target. We assumed an $A^{1/3}$ dependence for γ.

To analyze the η-production in hadron-deuteron collision we use the standard deuteron momentum distribution by Hulthen [14]

$$\Phi(q) = \frac{1}{(\alpha^2 + q^2)^2(\beta^2 + q^2)^2} \quad (5)$$

that is the squared Fourier transformation of the deuteron wave function

$$\psi(r) = \frac{exp(-\alpha r) - exp(-\beta r)}{r} \qquad (6)$$

where α=0.305 fm^{-1} and β=2.5α.

In the framework of the FCM the η-production cross section is given by

$$E_\eta \frac{d^3\sigma_{hA\to\eta X}}{d^3p_\eta} = N_1 \int d^3q \Phi(q) E'_\eta \frac{d^3\sigma_{hN\to\eta X}(\sqrt{s})}{d^3p'_\eta} \qquad (7)$$

where $\Phi(q)$ is the momentum distribution of the nuclear nucleons, N_1 is the first chance collisions number, $\sqrt{s}$ is the invariant energy of the incident proton-nucleon system and primed indices denote the η-meson momentum and energy in this p+N system, q is the nucleon momentum. In formula $d^3\sigma_{hN\to\eta X}(\sqrt{s})/d^3p_\eta$ stands for the elementary η differential cross section in collisions of hadrons with free nucleons. For η-production in proton-nucleus collisions we use a phase space calculation for reaction (1) and the η-production cross section suggested in Ref.[9].

The cross section for η-production in pion-free nucleon collision is parameterized by experimental data [15] as

$$\sigma_{\pi N\to\eta X}(\sqrt{s}) = \frac{A(\sqrt{s}-\sqrt{s_0})}{B+(\sqrt{s}-\sqrt{s_0})^2} \qquad (8)$$

where $\sqrt{s_0}$ is the threshold invariant energy and A and B are adjustable parameters. We use A=0.268 mbGeV and B=0.0017 GeV^2 suggested in Ref.[8]. To describe the differential cross section of reaction (2) we use $d\sigma/d\Omega^*_{\pi N\to\eta N}$ parameterization suggested by Brown et al [16] to describe the experimental angular distributions. The first chance collision number was calculated by Glauber and Matthia [17].

2.2 Two-body reaction mechanism

A different way to explain the production of mesons at subthreshold energies is the two-step reaction picture. The production of pion in a first collision of the incident proton with a nuclear nucleon followed by a pion-nucleon interaction is assumed

$$p + N_1 \rightarrow N + N + \pi \qquad (9)$$

$$\pi + N_2 \rightarrow \eta + N \qquad (10)$$

The importance of the secondary pion-nucleon reaction channel for subthreshold K^+ and η-production in proton-nucleus collision was found by Cassing et al. [6].

The η-production cross section in two-step processes taking into account the internal motion of the nucleons is given by:

$$E_\eta \frac{d^3\sigma_{pA\to\eta+X}}{d^3p_\eta} = \iint d^3q\, d^3p_\pi\, F(p_\pi)\, W(p_\pi, A)\, \Phi(q)\, E'_\eta \frac{d^3\sigma_{\pi N\to N\eta}(\sqrt{s})}{d^3p'_\eta} \qquad (11)$$

where $W(p_\pi, A)$ is the probability that pions produced in the first collision are rescattered in the target nucleus, $F(p_\pi)$ is the spectrum of pions produced in the first proton-nucleon collision and $\Phi(q)$ is the nucleon momentum distribution.

$E_\eta\, d^3\sigma_{\pi N\to N+\eta}(\sqrt{s})/d^3p_\eta$ is the elementary differential cross section for η-meson production in pion-nucleon collisions and was calculated as mentioned above.

The pion spectrum in Eq.11 is calculated in the framework of FCM as

$$F(p_\pi) = \int d^3q\; \Phi(q) E'_\pi \frac{d^3\sigma_{pN\to NN\pi}(\sqrt{s})}{d^3p'_\pi} \frac{1}{\sigma_{tot}(p+N)} \qquad (12)$$

where $E_\pi d^3\sigma_{pN\to NN\pi}(\sqrt{s})/d^3p_\pi$ is the elementary pion differential cross section and $\sigma_{tot}(p+N)$ is the total proton-nucleon cross section.

The pion-production cross section was taken from the compilation of experimental data by Flaminio et al. [15] and the differential cross section is assumed to be isotropic in the p+N center of mass system and completely determined by energy and momentum conservation.

By analogy with Ref.[9] we consider

$$W(p_\pi, A) = \frac{R^2 - \lambda^2/4}{R^2} \qquad (13)$$

where $R = 1.2A^{1/3}$ fm is the radius of the target with mass number A and

$$\lambda = \frac{1}{\sigma_{pN}\langle\rho\rangle} + \frac{1}{\sigma_{\pi N}\langle\rho\rangle} \qquad (14)$$

where $\langle\rho\rangle$ is average nuclear density and σ_{pN}, $\sigma_{\pi N}$ are the cross sections of pN and πN interactions.

Paoli et al [5] found that in heavy ion collisions the essential contribution to subthreshold η-production is due to the secondary Δ-resonance rescattering. Because of the creation of the high nuclear density in nucleus-nucleus collision the Δ undergoes the secondary interactions with both projectile and target nucleons before the Δ-decay. In proton-nucleus collisions we consider a normal nuclear density and expect that Δ-resonance decay before the farther rescatterings in nuclear media. To analyse the Δ-production channel we also take account for the following reactions

$$p + N_1 \rightarrow N + \Delta \qquad (15)$$

$$\Delta + N_2 \rightarrow N + N + \eta \qquad (16)$$

The important role of the secondary pion induced reaction associated with the deuterons was shown in the study on subthreshold K^+-production by Sibirtsev and Büscher [18]. It was found that $p + N -> d + \pi$, $\pi + N \to K^+ + \Lambda$ channel takes about 30% of the total K^+ production cross section at bombarding energies below 1 GeV. In order to analyze the contribution of the discussed reaction mechanism to the subthreshold η-meson production we consider the following process

$$p + N_1 \rightarrow d + \pi \qquad (17)$$

$$\pi + N_2 \rightarrow N + \eta \qquad (18)$$

The importance of this two-body production mechanism for the p+d$\to \eta+{}^3$He reaction was suggested by Kilian and Nann [19]. Obviously due to the final state interaction the deuteron and nucleon can fuse the ^{3}He nucleus.

2.3 η reabsorption

η-mesons are reabsorbed in nuclear environment via the excitation of the $N^*(1535)$ resonance that lead to strong distortions of the primordial η-production cross section and spectra. In order to account for η-reabsorption we use the ηN cross section evaluated by Bhalerao and Liu [20]

$$\sigma(\eta N, k) = 4\pi(Re a_{\eta N}^2 + Im a_{\eta N}^2) + 4\pi/k_\eta Im a_{\eta N} \tag{19}$$

where $a_{\eta N}$ = 0.27 + i 0.22 fm and k_η denotes the η-momentum in the N^* rest system. To take into consideration the internal motion of the nuclear nucleon we average ηN-cross section by the internal motion.

The η-reabsorption factor is then calculated according to assumption on uniform distribution of produced η-mesons inside the nucleus volume [8]

$$\kappa(T_\eta, A) = \frac{\pi \rho r_0^3}{y}(1 - \frac{1}{2y^2}(1 - (1 + 2y)exp(-2y)) \tag{20}$$

where y=$\rho\sigma$R and ρ=0.16 fm^{-3} is the normal nuclear density, $R = r_0 A^{1/3}$ is the nuclear radius, r_0 = 1.2 fm and σ is the averaged ηN-cross section. In Tab.1 we show the reabsorption factor calculated for carbon target and for several values of $\sigma_{\eta N}$.

A rather simple geometrical model for η reabsorption was suggested by Cassing et all [9]. Obviously the mean-free-path for η interaction at normal nuclear matter density is extracted via

$$\lambda_\eta(T_\eta) = \frac{1}{\sigma_{\eta N}(T_\eta)\rho} \tag{21}$$

and the reabsorption factor is calculated as

$$\kappa(T_\eta) = exp(-R/\lambda_\eta(T_\eta)) \tag{22}$$

It is clear (Tab.1) that for carbon target the reabsorption factor calculated by the simple geometrical model is of about an order of magnitude less than the factor κ calculated via Eq.20. Both suggestions on the η-reabsorption are quite crude, that escape us to analyse the data on η-meson production on nuclear targets with sufficient accuracy and reliance.

The detailed calculation by means of the cascade model [21] for η-interaction inside the nucleus results the following parameterization for the reabsorption factor

$$\kappa(A, \sigma_{\eta N}) = (3.9 - 0.024\sigma_{\eta N})A^{-2/3} \tag{23}$$

that does not agree with the assumptions above, that is shown in Tab.1.

To understand the discrepancies discussed above we need the accurate analysis on η reabsorption in nuclear media. For this purpose the detailed study on A-dependence of the production of η-mesons with different kinetic energies corresponded to $\sigma_{\eta N}$ is necessary.

3 Comparison with experimental data

We calculate η-production cross section in proton- and pion-nucleus collision by means of the models considering the direct and two-step η-production. For pion induced reaction only the First Collision Model (FCM) taking account the different momentum distributions of the nuclear nucleons was applied. For proton induced reaction we use FCM as well as Two Step Model (TSM) and take into consideration the reaction channels discussed. The calculated results are compared with the experimental data on η- production in πA-collisions measured at LAMPF [22] and the data on pA-collisions by SATURNE [4, 23].

3.1 Pion induced reaction

In Fig.1 we show the cross section for η-meson production in $\pi + {}^{12}C$-collision measured at angles less than 30° for different incident pion momenta. The solid curve show the FCM calculation taking account for standard Fermi-gas momentum distribution, whereas the dashed curve show the result for high momentum component. The calculated results are not corrected by the η reabsorption factor, that have decrease the η yield up to a factor of five already for ${}^{12}C$ target. Nevertheless the experimental data are well described except the deep subthreshold point. At incident pion momenta below 600 MeV/c the importance of the extreme momentum component is obvious.

The energy spectrum of η-mesons produced in pion-deuteron collisions at incident momentum of 680 MeV/c is shown in Fig.2. The deuteron target is very crucial for the analysis of the direct production mechanism because of the two reason. First, the η-reabsorption in deuteron target is negligible and there is no distortion of the primordial η spectrum. Thus we can study the production mechanism directly and neglect the nuclear influence except of the internal motion. Second, the contribution of the cascade reaction channels, particularly the two-step mechanism is suppressed by a factor of ten. The η-meson spectrum calculated with Hulthen function (solid line) fine reproduces the experimental one. By the dashed line we show the spectrum calculated for Fermi-gas momentum distribution that evidently does not fit the data.

In Fig.3 we show the η-energy spectrum produced in $\pi + {}^{12}C$ collisions at 680 MeV/c. Dashed (x) and dotted lines show the FCM results for Fermi-gas and high momentum functions respectively. The experimental data are not reproduced at whole. By solid line (a) we show the results for Hulthen function with the parameters adjusted for carbon target [14]. By solid curve (b) we show the Hulthen results corrected by the η-reabsorption factor that was calculated by means of the Eq.20. The experimental data on η-production in $\pi + {}^{12}C$ collisions are reasonably reproduced by FCM calculations with Hulthen function taking into account the η-reabsorption via the assumption (20).

We conclude that the shape of η-meson energy spectrum is very sensitive to the type of the nuclear nucleon momentum distribution. The energy spectra seem to be promising tool to study the both η-production mechanism and the nuclear wave function.

3.2 Proton induced reactions

In proton-nucleus collision the η-mesons are produced via both the direct and two-step mechanisms. In Fig.4 we show the experimental data on η-production cross section in $p^{12}C$-collisions measured at η-meson energies from 30 to 100 MeV and for production angles less than 40°. By solid line we show the FCM result calculated with Fermi-gas momentum distribution whereas the dashed line show the contribution from the high momentum distribution. Also we have not account for η-reabsorption, that decreases the original cross section remarkably, the experimental data are underestimated. In Fig.5 we show the TSM results taking into consideration the reaction mechanisms discussed. The solid line shows the contribution of the πNN-channel and the dashed one stands for the πd-channel. By the dotted line we show the results for intermediate delta production, that strongly contribute to η-production in heavy ion collisions. We notice that for the proton-nucleus collision the Δ resonance channel is not important.

The η energy spectrum produced in p + ^{11}B-collisions at proton energy of 1 GeV is shown in Fig.6. By solid line we show the FCM results calculated with Fermi gas model function. The result calculated by FCM taking account for high momentum distribution is shown by the dashed curve. In Fig.7 we show the TSM results calculated for πNN (solid line) and πd channels (dashed line). We do not correct the calculated results for η-reabsorption.

4 Conclusions

At this stage we summarize, that measured η- cross section as well as energy spectra produced in pion-nucleus collisions at LAMPF are well reproduced by the FCM considered the direct η production in proton- nuclear nucleon collision. The energy spectra are very sensitive to the internal motion function applied. The problem is the description of the deep subthreshold η-production at incident pion momenta below 600 MeV/c. At this moments we need for high momentum component of the nuclear wave-function to describe the data. Unfortunately we have one experimental point only at momentum region of interest. And we have not η-energy spectra at bombarding momentum below 680 MeV, that seem to be very crucial for the direct production channel.

The experimental data on η-production in proton-nucleus collision obtained at SATURNE are not reproduced by the models considering the possible η-production mechanisms. The reaction mechanisms involved in the analysis are quite adequate in the description of the experimental data on subthreshold π-, K^+- and antiproton production in pA-collisions but seem failure to reproduce the experimental data on η-production in proton induced reactions.

The found discrepancies may be considered via the two essential reasons. First is the η-reabsorption via the excitation of the N*(1535) resonance. It is not entirely understood and also there is not common approach to describe the ηN-interactions in nuclear environment. To study the problem the A-dependence on the production of η-mesons with different kinetic energies is necessary. Second is the kinematical limitation of the experimental data on η production in proton-nucleus collision. The data were collected within 40° angular and 70-100 MeV energy region. Thus we have to analyse the data obtained at strongly restrictive phase space region, that essentially complicates the calculations because one requires the detailed knowledge on the η production amplitudes.

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$\sigma_{\eta N}$ mb	40	60	100
Eq.20	0.43	0.31	0.19
Eq.22	0.17	0.07	0.01
Eq.23	0.56	0.47	0.29

Table 1: η reabsorption factor calculated by means of different approaches for ^{12}C target.

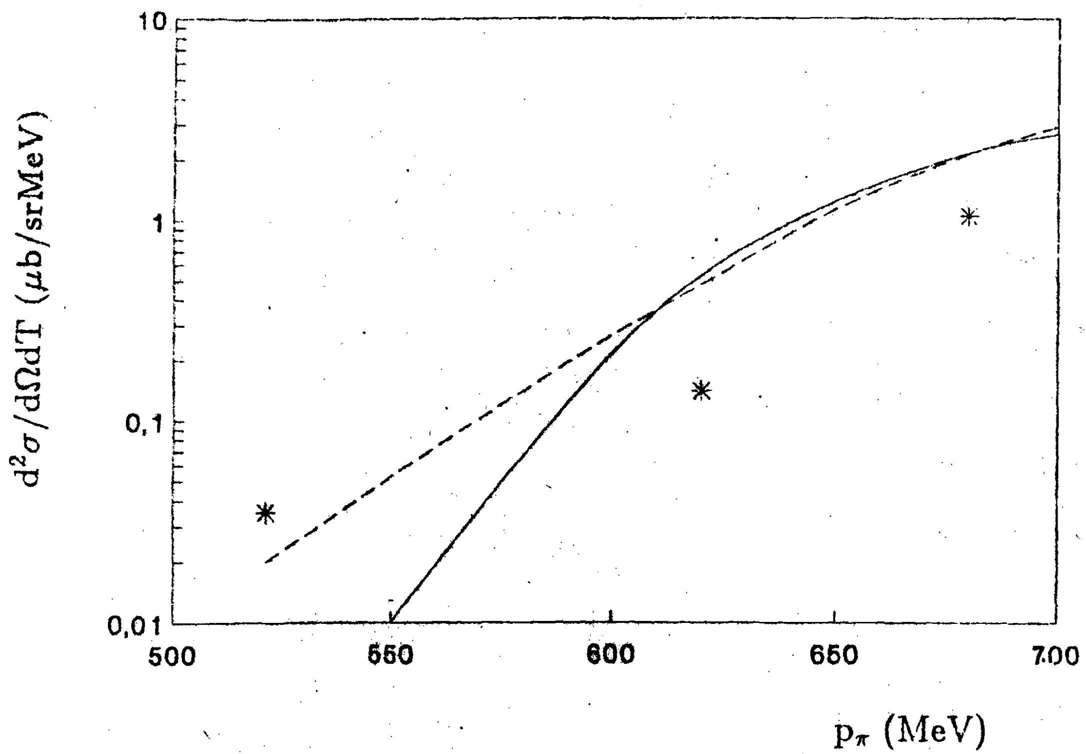

Fig.1. η-meson production cross section produced in π + ^{12}C collisions as a function of pion momentum. The experimental points are from LAMPF. The line show FCM results calculated with Fermi (solid) and high momentum functions (dashed).

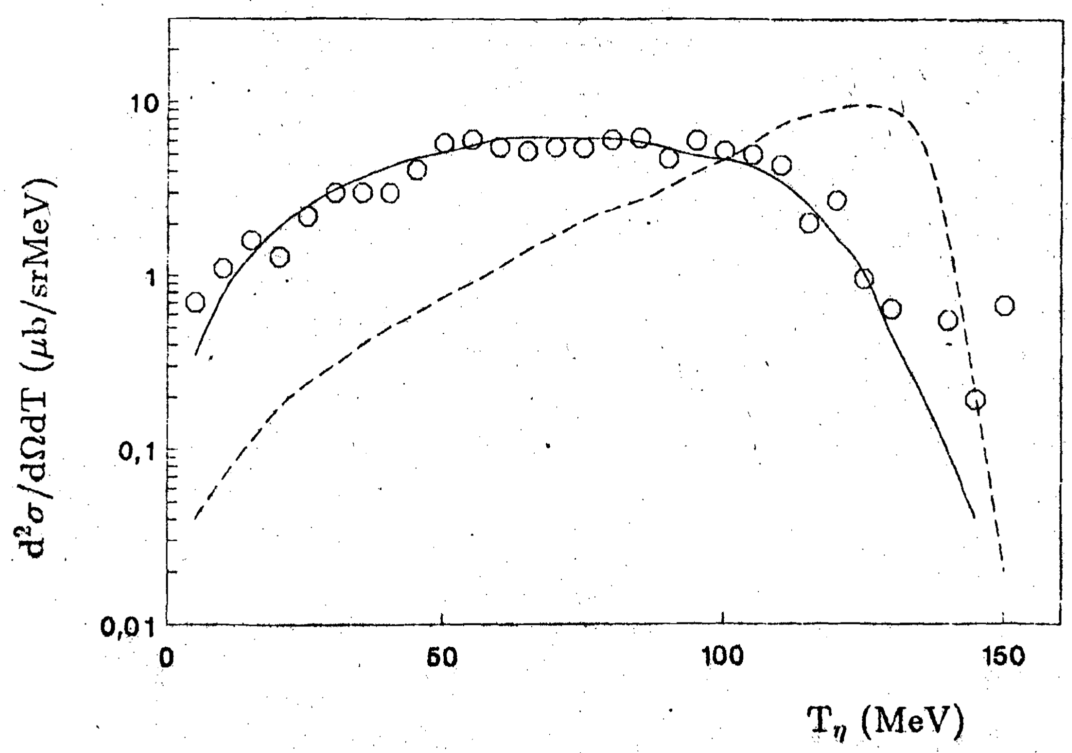

Fig.2. η-energy spectrum produced in π + d collisions at 680 MeV/c. The solid line shows FCM results with Hulthen function, dashed - Fermi.

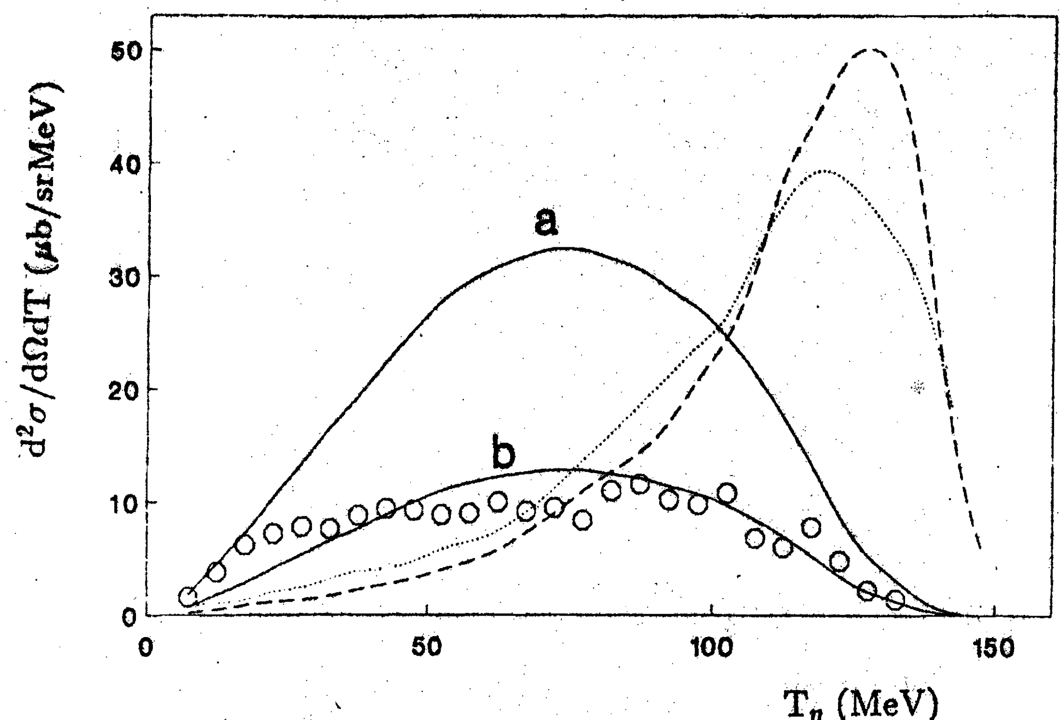

Fig.3. η-energy spectrum produced in $\pi + {}^{12}C$ collisions at 680 MeV/c. Lines show FCM calculations with Fermi (dashed), high momentum (dotted) and Hulthen functions (solid a) without η-reabsorption. Solid line (b) denotes Hulthen results with η-reabsorption.

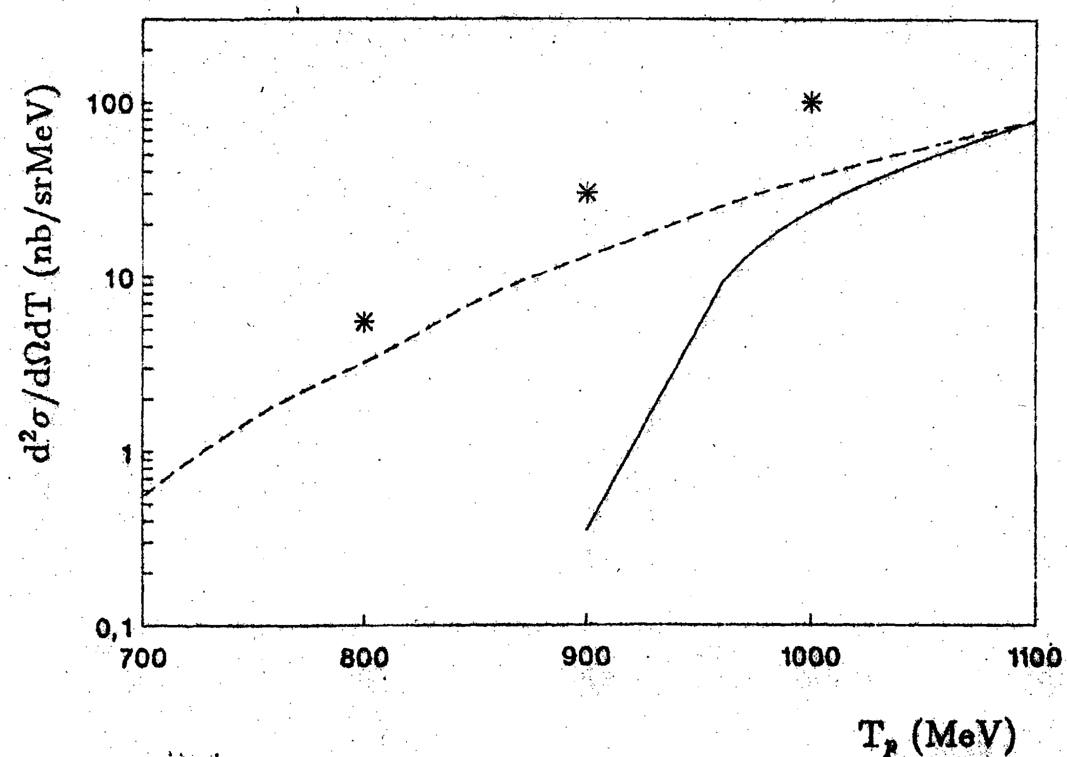

Fig.4. η-production cross section in $p + {}^{12}C$ collisions as a function of bombarding energy. The experimental points are from SATURNE. Lines show FCM calculations with Fermi (solid) and high momentum functions (dashed).

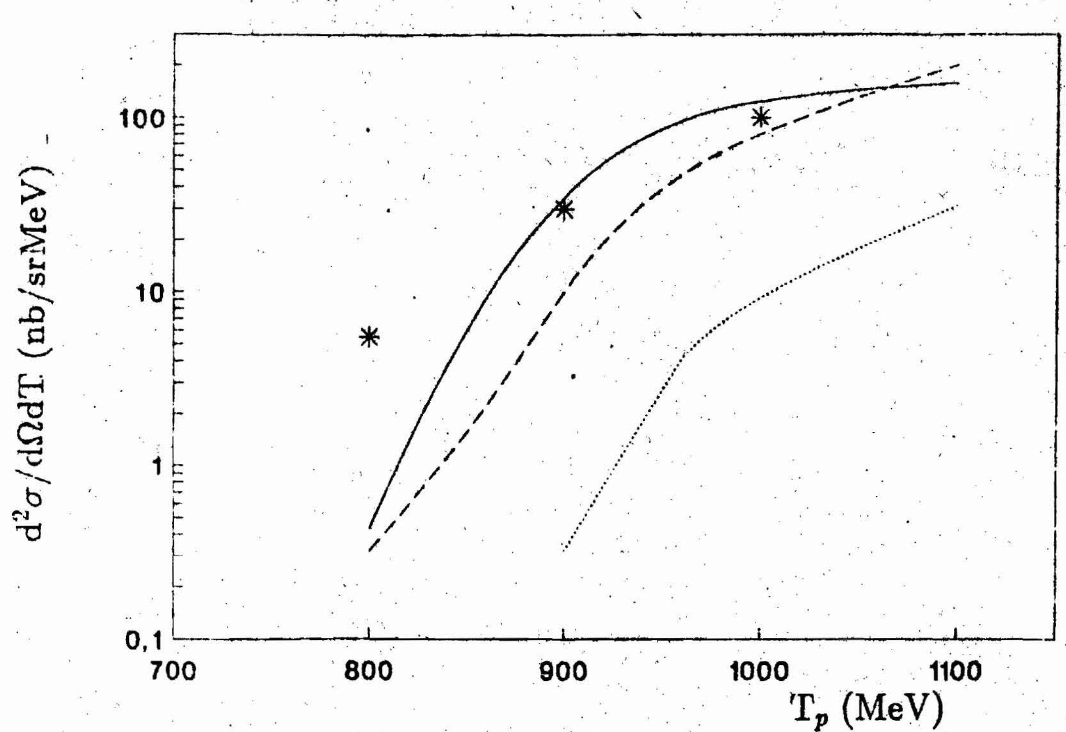

Fig.5. η-production cross section in p + ^{12}C collisions. Lines show TSM results calculated for $NN\pi$ (solid), πd (dashed) and $N\Delta$ channels (dotted).

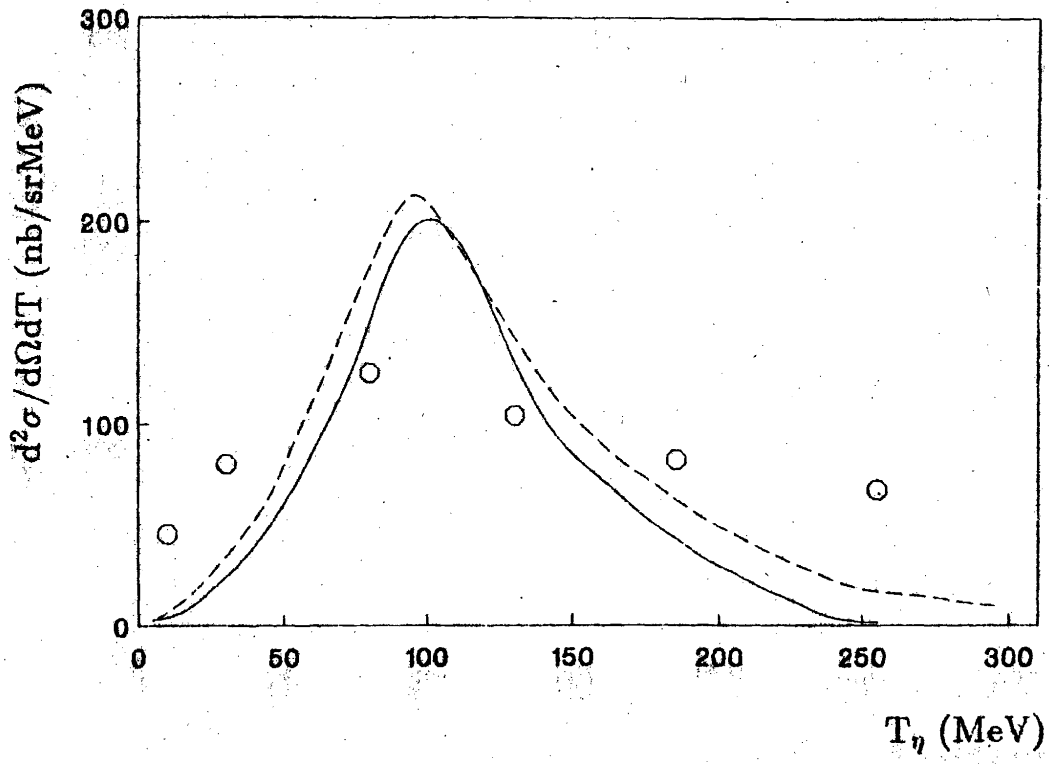

Fig.6. η-energy spectrum produced in p + ^{11}B collisions at 1 GeV. Points are from SATURNE. Lines show FCM results for Fermi (solid) and high momentum functions (dashed).

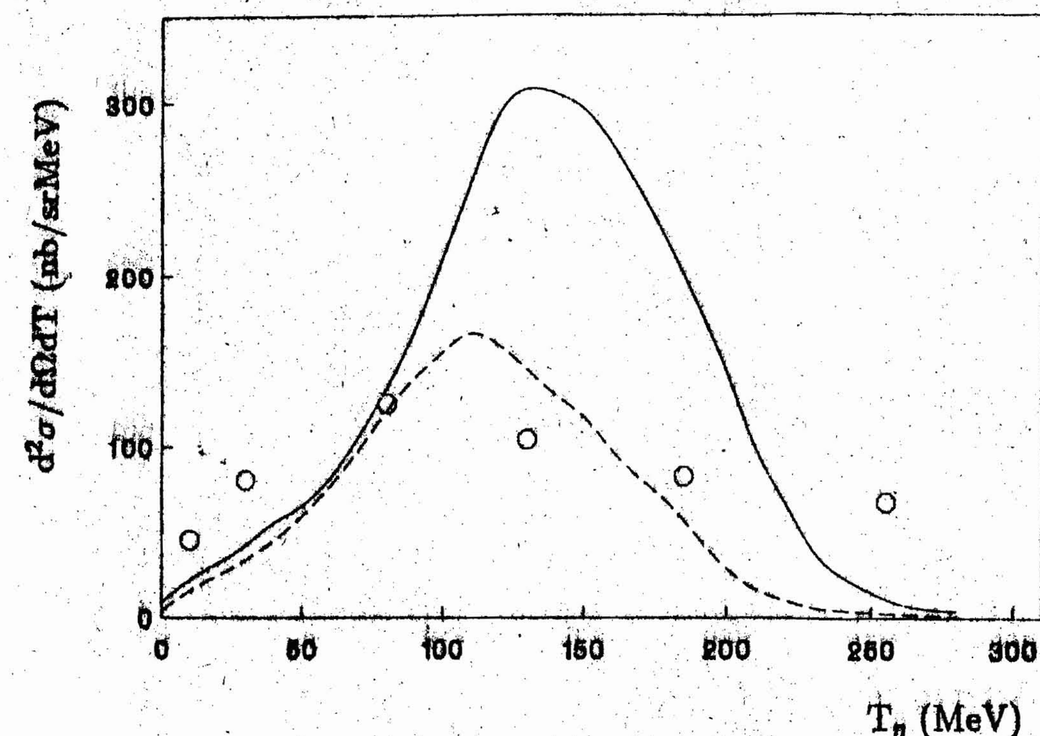

Fig.7. η-energy spectrum produced in $p + {}^{11}B$ collisions at 1 GeV. Lines show TSM results calculated for for $NN\pi$ (solid) and πd reaction channels (dashed).

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А.А.Сибирцев
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