ON INTERPRETATION OF CUMULATIVE PROCESSES IN THE "GATHERING" MODEL

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Papers of Kalinkin, Shmonin et al. describing cumulative meson production in hadron-nuclear and nucleus-nuclear interactions have been analysed, and the results of this critical analysis are given. It is shown that there are many errors in the calculation formulae. The attempts to reproduce the numerical results of the authors from their formulae and their computer programme gave no positive results.

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It is well known that the majority of theoretical models proposed by various groups of authors [1-3] for interpretation of experiments on cumulative meson production in hadron-nuclear and nucleus-nuclear collisions cannot provide a self-consistent description of all the available experimental information. Only the "gathering" model developed for several years by Kalinkin, Shmonin et al. [4-9] has been supposedly successfully describing all experimental data [10-14]. At least this is how the authors try to represent the situation. All their calculated curves for production of cumulative pions in pA and $C^{12}A$ collisions are practically inside the corridor of experimental errors thus showing a "good" description of the experiment by the "gathering"model.

Noteworthy is that this striking success was achieved with a minimum of means, namely, with a proper choice of the values of only two parameters of the model $\sigma_c = 10$ mb and $\tau_0 = 2^{\text{fm} \cdot \text{GeV}/c}$ [1]. Their integer values without allowance for errors make one think that they are not obtained by fitting the experimental data, but are chosen by the "rule of thumb".

The programme of numerical calculations published in the last paper of the cycle [8] helps us to understand the success of the model. Reznik and Titov [15] tried to use the programme for finding out how the authors of the model had managed to get a consistent

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[1] The physical meaning of these parameters is discussed below.

description of yields of cumulative π- and K-mesons in proton-nuclear interactions at $E_0 = 8.9$ GeV. We shall only mention one conclusion of this paper: the optimistic claim of the authors of the "gathering" model that it also describes production of cumulative K-mesons "fairly well with an accuracy of a factor of 1.5–2" contradicts the results obtained with the help of their own numerical calculation programme: actually, the calculated values differ from the experimental ones by a factor of 30. If this were the only fact in authors' practice of achieving agreement between the model and experiment, one could try to find

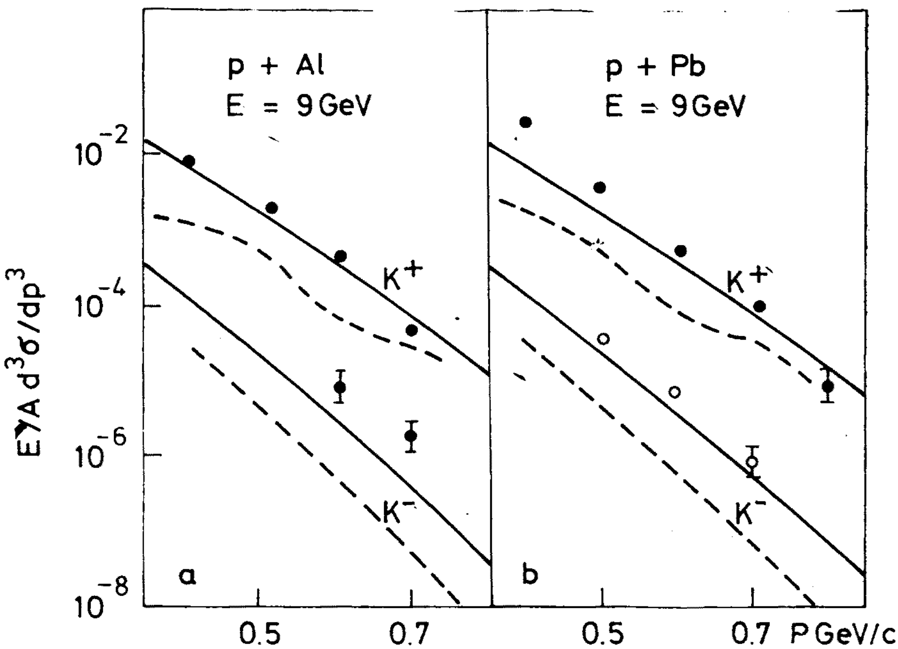

Fig. 1. [6, 8, 9] $\frac{E}{A}\frac{d\sigma}{d\vec{p}}$ for pTa → $\pi^{\pm}$X at $E_p = 8.9$ GeV; (a) Al, (b) Pb

a reasonable explanation of it. A detailed comparison of the numerical results obtained by means of the above-mentioned programme with the corresponding figures in the papers of the authors of the "gathering" model shows, however, that drawing calculated values up to experimental points is more the rule than an exception in the discussed papers.

Let us illustrate this with several examples. Figures 1–3 show some results of our calculations (dashed lines) performed by the computer programme [8] in comparison with the author's results (solid lines) and experimental data. It is necessary to say that in the cases when we calculated the same characteristics as in the paper by Reznik and Titov our results were consistent with their results but not with the results of Kalinkin, Shmonin et al. (see, for example, Fig. 1). Fig. 2 shows results of calculation of the cumulative pion yield in the reaction pTa → π^-X at $E_p = 400$ GeV and $\theta = 118°$. In the papers [6, 8, 9] the same figure presents the data at $\theta = 118°$ and $\theta = 160°$ with the curves passing through experimental points. This figure shows, according to the authors, that the "gathering"

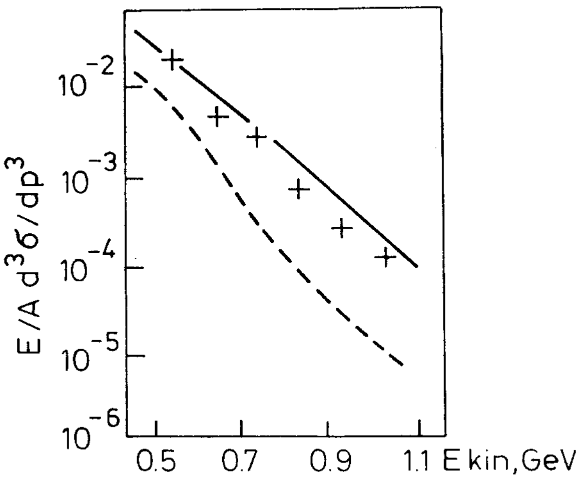

Fig. 2. [6, 8, 9] $\frac{E}{A}\frac{d\sigma}{d\vec{p}}$ for pTa $\rightarrow \pi^-X$ at $E_p = 400$ GeV, $\theta = 118°$

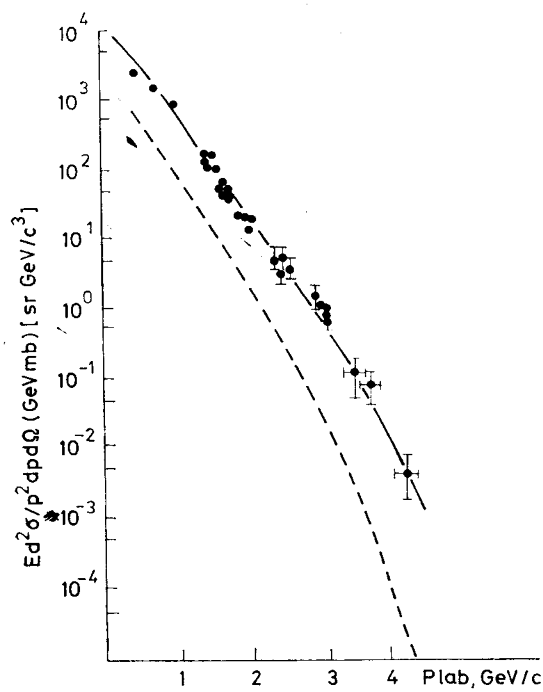

Fig. 3. [7–9] $E\frac{d\sigma}{d\vec{p}}$ ($\theta = 0°$) for π^- mesons in the process CC $\rightarrow \pi^-X$ at $E_0 = 3$ GeV/nucleon

model successfully describes the angular dependence of the cumulative pions yield. We succeeded in reproducing the authors' calculations for $\theta = 160°$. As for $\theta = 118°$ the situation is as depicted in Fig. 2. In the paper [7] "gathering" model is generalised for description of cumulative meson production in nucleus-nuclear interactions and a figure is presented. In accordance with this figure the model reproduces the absolute value of the cumulative pions yield in αC and CC interactions at $E_0 = 3$ GeV/nucleon at $\theta = 0°$. The results of our calculations[2] are compared with the authors' ones in Fig. 3. It seems to us that these examples together with the results of the paper [15] are a convincing demonstration of the methods used by the authors of the "gathering" model to achieve agreement between theory and experimental data.

Above we have briefly touched upon the external part of the model which deals with the degree of its agreement with the experiments, the methods of achieving such a good agreement by the authors. It is also interesting to have a look at the internal part of the model, i.e. the correspondence between its verbal formulation and realisation in the form of working formulae.

First, let us briefly present the verbal formulation of the "gathering" model. It is based on the assumption that the production process of cumulative particles in hadron-nuclear interactions has two stages. At the first stage, a massive unstable compound system is produced in a nucleus affected by an incident hadron. This system contains several (n) nucleons of the nucleus. At the second stage it decays and among decay products there are cumulative particles. Production of the compound system is also a multistage process. First, the hadron excites a nuclear nucleon to the state of the "cluster" transferring approximately a half of its 4-momentum to it according to the value $k = 0.5$ of the mean inelasticity coefficient in hadron-nucleon collisions. Moving through the nucleus this excited nucleon can unite with another nuclear nucleon (pick it up) according to kinematics of the absolutely inelastic collision and a more complex compound system is formed; it comprises two nuclear nucleons. Owing to the same "picking-up" mechanism the two-nucleon cluster can form a three-nucleon cluster and so on. The cross sections both for excitation of the nucleon to the "cluster" state by the incident hadron and for further "gathering" processes are the same and equal to $\sigma_c = 10$ mb, according to the authors. This is one parameter of the model.

To clarify its second parameter τ_0, we have to quote the authors [5]: "At the same time σ_c cannot be the only parameter of cumulation. In fact, the compound system formed can immediately decay with emission of an energetic particle, or its energy can manage to dissipate over many internal degrees of freedom, which in future leads to production of "soft" particles. In both cases the system is lost for the "cumulative process", and then: "survival" of the states capable of emitting cumulative particles in relation of processes of both the decay of the whole system and energy dissipation over other degrees of freedom

[2] Strictly speaking, the programme [8] only related to cumulative meson production in hadron--nuclear interactions. It can be shown, however, that the expressions from Ref. [7] for the cross sections of the processes $A_1A_2 \rightarrow MX$ can be represented as a product of the expressions [7] for the cross sections of the processes $pA_1 \rightarrow MX$ and the effective number of nucleons $N_1(A_2, \sigma_{in}^{NN})$ in the nucleus A_2.

can be given by the usual exponential function:

$$\eta_{c.m.} = \exp(-t/\bar{\tau}_0). \tag{1}$$

Then it is assumed that $\bar{\tau}_0$ is inversely proportional to the mass M of the compound system: $\bar{\tau}_0 = \tau_0/M$ where $\tau_0 = 2^{\text{fm}\cdot\text{GeV}/c}$. The latter is the second parameter of the model.

Let us sum it up. The hypothetical compound systems formed in a nucleus affected by the incident hadron are supposed to be non-equilibrium states. These systems can decay with emission of cumulative particles only at the initial stage of their evolution, being in a highly non-equilibrium state. In future, the authors will call this state a "coherent" one [7]. "Coherent" states of more complex compound systems, i.e. those with a greater number of nuclear nucleons can be produced by less complex compound systems only if they are in the "coherent" state[3]. It is evident that the description of cumulative meson production within the framework of the model under discussion requires to give two time parameters for each compound system: $\bar{\tau}_1$ — the mean lifetime of a compound system; $\bar{\tau}_2$ — the mean time necessary for establishing thermodynamic equilibrium in it (or "hadronisation" as the authors call it) that results in the system energy "dissipation over many degrees of freedom", and the system looses a possibility of decaying with emission of energetic cumulative particles.

Thus, the factor $\eta = \exp(-t/\bar{\tau}_0)$ is a product of the probability $\eta_1 = \exp(-t/\bar{\tau}_1)$ for the unstable system not to decay in a time t in its rest frame by the probability $\eta_2 = \exp(-t/\tau_2)$ for this system to remain in the "coherent" state. An evident relation between $\bar{\tau}_1$, $\bar{\tau}_2$ and $\bar{\tau}_0 = \tau_0/M$ follows:

$$1/\bar{\tau}_0 = 1/\bar{\tau}_1 + 1/\bar{\tau}_2. \tag{2}$$

The expressions in Refs [4–9] for cross sections of cumulative meson production only depend on these combinations of the quantities $\bar{\tau}_1$ and $\bar{\tau}_2$ for each compound system. And this is the first qualitative indication that they are not correct.

In fact, the number of compound systems decaying over the "cumulative" channel is evidently equal to

$$R = \bar{\tau}_2/(\bar{\tau}_1+\bar{\tau}_2) = \bar{\tau}_0/\bar{\tau}_1$$

and the contribution from the decay of the corresponding compound system to the cross section of cumulative meson production must be proportional to this quantity. The formulae of the authors of the "gathering" model do not contain such quantities, and numerical values of parameters $\bar{\tau}_1$, which are as necessary for obtaining these quantities as the values of parameters $\bar{\tau}_0 = \tau_0/M$ are not specified in any of their papers.

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[3] In common sense, one should take into account the contribution of "semicoherent" states (i.e. intermediate states between absolutely "coherent" and absolutely "incoherent", or equilibrium, ones) to cross sections for production of cumulative particles and for decay processes. The authors do not, however, even discuss such details of their model. According to their scheme, thermodynamic equilibrium is established in a jump.

To understand how the authors manage to do with one time parameter τ_0, we have to formulate some formulae realising the physical pattern of cumulative meson production described above in words.

It is evident that in this model the observed spectra of the cumulative particles of sort a must be represented by the superposition

$$E_a \frac{d\sigma}{d\vec{p}_a} = \sum_n \tilde{\sigma}_A^{(n)} \cdot E_a \frac{dW^{(n)}}{d\vec{p}_a} \tag{3}$$

of decay spectra $E_a \frac{dW^{(n)}}{d\vec{p}_a}$ where $dW^{(n)}$ is the differential probability of the decay of the n-th compound system with some weights $\tilde{\sigma}_A^{(n)}$ which have dimensions of cross sections. The physical meaning of the latter should be discussed separately. The structure of quantities $\sigma_A^{(n)}$ must evidently reflect the following principles: a) production of the "coherent" state of a compound system of index n at some point inside the nucleus, and b) its decay over the "cumulative" channel at an arbitrary point of space on the trajectory of the system. Integration should be carried out over possible points of compound system production and decay. Assuming with the authors of the model that all compound systems move along rectilinear trajectories with a common value of the impact parameter $\vec{b}$ which coincides with the value of the impact parameter of the incident hadron, we represent the quantities $\tilde{\sigma}_A^{(n)}$ by

$$\tilde{\sigma}_A^{(n)} = \int d\vec{b} dz_1 dz_2 \theta(z_2 - z_1) \omega_p^{(n)}(\vec{b}, z_1) \omega_d^{(n)}(\vec{b}, z_1, z_2). \tag{4}$$

Here $\omega_p^{(n)}(\vec{b}, z_1)$ is the differential probability of production of the n-th compound system on a unit path of the $(n-1)$-th compound system, which produces the former one, at the point with coordinates $\vec{b}, z_1$; $\omega_d^{(n)}(\vec{b}, z_1, z_2)$ is the differential probability of its decay on its unit path at the point with coordinates $\vec{b}, z_2$ under an additional condition that before the decay, i.e. in the interval $z_2 - z_1$ this compound system remained in the "coherent" state and had no inelastic interactions with the nuclear matter which could change its energy characteristics and, consequently, energy characteristics of decay products or make for its conversion into a more complex compound system.

The expression for $\omega_d^{(n)}(\vec{b}, z_1, z_2)$ has the form:

$$\omega_d^{(n)}(\vec{b}, z_1, z_2) = \frac{1}{l_1^{(n)}} \cdot \exp\left[-(z_2 - z_1)\left(\frac{1}{l_1^{(n)}} + \frac{1}{l_2^{(n)}}\right)\right]$$

$$\times \exp\left[-\sigma_{in}^{nN} \int_{z_1}^{z_2} \varrho(\vec{b}, z') dz'\right]. \tag{5}$$

Here σ_{in}^{nN} is the summed cross section for inelastic interactions between the n-th cluster and the nucleon, $\varrho(\vec{b}, z)$ is the density of the nuclear matter normalized to the mass number A, $l_i = \bar{\tau}_i \cdot v^{(n)} \gamma^{(n)}$ $(i = 1, 2)$, and $v^{(n)}$, $\gamma^{(n)}$ are the velocity and the Lorentz factor of the n-th cluster in the lab. system.

The quantities $\omega_p^{(n)}(\vec{b}, z)$ obey the following recurrence relations

$$\omega_p^{(n)}(\vec{b}, z) = \int_{-\infty}^{z} \omega_p^{(n-1)}(\vec{b}, z')\sigma_c^{(n-1)} \cdot \varrho(\vec{b}, z')dz'$$

$$\times \exp\left[-(z-z')\left(1/l^{(n-1)}+1/l^{(n-1)}\right)-\sigma_{in}^{n-1,N} \int_{z'}^{z} \varrho(\vec{b}, z')dz'\right] \tag{6}$$

the initial condition being

$$\omega_p^{(0)}(\vec{b}, z) = \sigma_c^{(0)}\varrho(\vec{b}, z) \exp\left[-\sigma_{in}^{hN} \int_{-\infty}^{z} \varrho(\vec{b}, z')dz'\right], \tag{7}$$

where $\sigma_p^{(n-1)}$ is the cross section for the "gathering" interaction of the $(n-1)$-th cluster i.e. for the process $(n-1)+N \to (n)$, and the superscript 0 is for the incident hadron[4]. We do not assume equality of all $\sigma_c^{(n)}$ here, the reason for this will be clear later.

Let us now compare our expressions for the weight coefficients $\tilde{\sigma}_A^{(n)}$ in relation (3) with the same quantities of the authors [4–9] which are denoted by $W_A^{(n)}$ in their papers. These quantities can be represented as:

$$W_A^{(n)} = \int \tilde{\omega}_p^{(n)}(\vec{b}, z)d\vec{b}dz. \tag{8}$$

The quantities $\tilde{\omega}_p^{(n)}(\vec{b}, z)$ obey recurrence relations (6) with the only difference that one always has $\sigma_{in}^{kN} = \sigma_c^{(k)} \equiv \sigma^{(k)}$ there. At the same time there are two types of expressions for $W_A^{(n)}$ in different papers of the cycle [4–9]. They differ by the choice of $\sigma^{(k)}$. In the earlier papers and the last ones there is always $\sigma^{(k)} = \text{const}\,(k) = \sigma_c = 10$ mb. In the papers [6–8] $\sigma^{(k)} = \sigma_c = 10$ mb for $k = 0, n-2$, and $\sigma^{(n-1)} = \sigma_{in}^{pN} = 32$ mb.

The last case is of special interest, since it implies that hadrons and compound systems appear to behave causally. No other explanation can be given to the fact that the same physical object (a hadron or a compound system) has different interaction properties when it is or is not the "last but one" in the chain whose final products, i.e. the n-th compound system decays producing cumulative particles. However, the authors make somewhat different comments on this. And these comments are curious enough. It turns out that replacing $\sigma^{(n-1)} = \sigma_c = 10$ mb as in previous papers by $\sigma^{(n-1)} = \sigma_{in}^{pN} = 32$ mb in Ref. [6] allows taking into account distributions over the inelasticity coefficient in pN-interactions. This is undoubtedly an original explanation, but it has nothing to do with physics. Let us return to the quantities $W_A^{(n)}$. The authors [5] call them the cross sections for production of the n-th compound system. In this connection one should remember that masses and velocities of all intermediate and the final compound system are regarded as strictly determined and only depending on the initial energy of the hadron, the mean value of its inelas-

[4] We omit the complications related to the presence of the internucleon core [6] as insignificant for the further discussion.

ticity coefficient and the number of nucleons "gathered" in the compound system. It is clear that fulfillment of this condition requires that neither the hadron before it produces the first cluster, nor the intermediate compound systems between their production and conversion into more complex compound system undergo any inelastic interactions and not only the "gathering" ones which can lead to measurement of their energy characteristics. Therefore, the indices of "absorbing" exponential functions in relations (5), (6) must be σ_{in}^{kN} and not $\sigma_c^{(k)}$ as in Refs [4–9].

In view of this the quantities $W_A^{(n)}$ of the authors do not have the meaning assigned to them in Refs [4–9], namely, that of cross sections for production of the n-th compound system. We shall further denote these cross sections by $\sigma_A^{(n)}$. It is clear that these quantities are larger than $\tilde{\sigma}_A^{(n)}$ and have a stronger dependence on the mass number A of the target nucleus. But even if there were no confusion concerning the "absorbing" exponential functions, and $W_A^{(n)}$ in fact coincided with $\sigma_A^{(n)}$, the authors, nevertheless, would have no right to employ it as weight factors in relation (3).

As a matter of fact, the use of $\sigma_A^{(n)}$ in this capacity is equivalent to an assumption that all compound systems of the n-th order will decay emitting the cumulative particle and never undergo any interactions including "gathering" ones, the dissipation processes being "frozen" inside them. A behaviour like this is again noncausal. We hope that even the authors of the model should not insist on the existence of physical objects with such exotic properties.

If one assumes a normal behaviour of compound systems, one must admit that the authors' quantities $W_A^{(n)}$ in the relevant expressions for spectra of cumulative particles must be replaced by the above-mentioned quantities $\tilde{\sigma}_A^{(n)}$.

Let us try to estimate the difference between them, at least, by the order of magnitude. For this purpose, let us take $\sigma_{in}^{nN} = 0$ in the expression for $\omega_d^{(n)}(\vec{b}, z_1, z_2)$. We neglect the nuclear "absorption" of the n-th compound system. This evidently leads to overestimation of values for $\tilde{\sigma}_A^{(n)}$. Integration over z_2 in (5) is explicit in this approximation, and we have

$$\tilde{\sigma}_A^{(n)} \leqslant R^{(n)} \cdot \sigma_A^{(n)}$$

where $R^{(n)} = l_2^{(n)}/(l_1^{(n)}+l_2^{(n)}) \equiv \bar{\tau}_0^{(n)}/\bar{\tau}_1^{(n)}$, and $\sigma_A^{(n)} = \int \omega_p^{(n)}(\vec{b}, z)d\vec{b}dz$ are the cross sections for production of the n-th compound system. With allowance for what is said above $\sigma_A^{(n)} < W_A^{(n)}$ and finally we have $\tilde{\sigma}^{(n)}/W_A^{(n)} < R^{(n)}$.

Since, as was mentioned, neither of the authors' papers specifies the values of $\bar{\tau}_1$, we shall try to obtain the upper estimate for $R^{(n)}$ on the basis of authors' claim that "the gathering model does not require taking into account absorption of cumulative particles by the nuclear matter, since, according to its logic, all compound systems mainly decay outside the nucleus [6, 8]". It follows that for all compound systems $\bar{l}_1 = \bar{\tau}_1 v\gamma \geqslant 2R_A \sim 10$—15 fm. On the other hand, for "cumulative" compound systems ($n \geqslant 2$) $\bar{l}_0 = \bar{\tau}_0 v\gamma \leqslant 0.5$ fm, according to the programme of numerical calculations. Hence we obtain $R^{(n)} \leqslant 3\text{–}5 \cdot 10^{-2}$ for $n \geqslant 2$. Thus, calculations using formulae (3)–(7) which, unlike the formulae in Refs [4–9], are in correspondence with the verbal formulation of the model, will make the situation in Fig. 1–3 even worse.

We have only touched upon few details of the "gathering" model. Together with the results of Ref. [15], this is enough to make a conclusion that the attempts of the authors of the model to represent it as the candidate and the only one for the physical pattern of cumulative processes seem not convincing.

REFERENCES

[1] L. P. Kaptar, B. L. Resnik, A. I. Titov, *Yad. Fiz.* **42**, 777 (1985); V. K. Lukyanov, A. I. Titov, *ECHAYA* **10**, 815 (1979).
[2] A. V. Efremov, *ECHAYA* **13**, 613 (1982).
[3] L. L. Francfurt, M. I. Strikman, *Phys. Rep.* **76**, 215 (1981).
[4] B. N. Kalinkin, A. V. Cherbu, V. L. Shmonin, *Acta Phys. Pol.* **B9**, 375, 385, 393 (1978).
[5] B. N. Kalinkin, A. V. Cherbu, V. L. Shmonin, *Fortschr. der Phys.* **27**, 35 (1980).
[6] E. S. Golubyatnikova, G. A. Shakhanova, V. L. Shmonin, *Acta Phys. Pol.* **B15**, 585 (1984).
[7] S. Sh. Ameev, V. L. Shmonin, Preprint HEPI 85–03, Alma-Ata 1985; *Acta Phys. Pol.* **B16**, 821 (1985).
[8] Yu. F. Gagarin, B. N. Kalinkin, V. L. Shmonin, Preprint FTI 976, Leningrad 1986.
[9] V. L. Shmonin, Preprint HEPI 85–09, Alma-Ata 1985.
[10] A. M. Baldin et al., Comm. JINR 1–12396, Dubna 1979.
[11] A. M. Baldin et al., Comm. JINR 1–80–488, Dubna 1980.
[12] A. M. Baldin et al., Comm. JINR E1–82–472, Dubna 1982.
[13] N. A. Nikiforov et al., *Phys. Rev.* **C22**, 2, 700 (1980).
[14] E. Moeller et al., *Phys. Rev.* **C28**, 1246 (1983).
[15] B. L. Reznik, A. I. Titov, Comm. JINR P2–87–37, Dubna 1987.