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A.A. Arkhipov

DIFFRACTION DISSOCIATION AND THREE-BODY FORCES AT HIGH ENERGIES

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Abstract

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It is shown that the experimental measurement of the one-particle inlcusive cross sections in the region off difffraction dissociation at high energies gives us a unique possibility to study the three-body forces.

Аннотация

Архипов А.А. Диффракционная диссоциация и трехчастичные силы при высоких энергиях: Препринт ИФВЭ 96-66. – Протвино, 1996. – 11 с., 3 рис., 1 табл., библиогр.: 19.

Показано, что экспериментальное измерение одночастичных инклюзивных сечений в области диффракционной диссоциации при высоких знергиях доставляет уникальную возможность исследования трехчастичных сил.

Introduction

In this paper I'd like to draw your attention to the fact that the experimental measurement of the inclusive cross sections in the region of diffraction dissociation at high energies gives us a unique possibility to study a new type of interactions or a new type of forces, namely the three-body forces. This point of view on the inclusive cross sections is unconventional and it has not been discussed in the literature.

I'll not claim to describe quantitatively the experimental data obtained in the investigations of the diffraction dissociation processes. I'd like only to discuss some physical and mathematical ideas which will allow us, I hope, to create a physically visual picture and representation for the diffraction dissociation processes at the same level as we can now understand and represent the elastic scattering processes at high energies.

Let me remind you the topic of my talk at the meeting "Hadrons-94" two years ago. I reported there on the asymptotic relation between the slope of diffraction peak in elastic scattering and the total cross section at high energies [1]. The relation looks like

$$\sigma_{tot}(s) = 2\pi B(s), \quad s \to \infty. \tag{1}$$

This relation is remarkable in many aspects. For instance, if we define the effective interaction radius by equality

$$B(s) = \frac{1}{2} R^2_{eff}(s), \tag{2}$$

then we obtain

$$\sigma_{tot} = \pi R^2_{eff}(s), \quad s \to \infty, \tag{3}$$

i.e. the total cross section is defined in this case by the geometric section of the sphere with the radius being equal to the effective interaction radius.

The statement can obviously be reversed i.e. if we define the effective interaction radius with the help of Eq. (3) then we obtain relation (2) for the slope of diffraction cone in elastic scattering.

Another peculiarity lies in the fact that the asymptotic relation (1) is of dynamical origin. The relation has been obtained from the analysis of high energy particle scattering from deuteron, and at the same time the generalized asymptotic theorems [9,10] a la Froissart [4] for many-body forces scattering amplitudes have been used.

The recent experimental data for $p\bar{p}$ scattering in the energy range $\sqrt{s} = 30-1800\,GeV$ show that the asymptotic relation (1) agrees with the experiment up to $30 - 40$ percent. That is why we come back to the derivation of relation (1) and try to find the main reasons for such bad agreement.

1. Three-body forces in relativistic quantum theory

Using the LSZ or Bogoljubov reduction formulae in quantum field theory [2] we can easily obtain the following cluster structure for $3 \to 3$ scattering amplitude (see Fig.1)

$$\mathcal{F}_{123} = \mathcal{F}_{12} + \mathcal{F}_{23} + \mathcal{F}_{13} + \mathcal{F}_{123}^{C} \tag{4}$$

where $\mathcal{F}_{ij}, (i,j = 1,2,3)$ are $2 \to 2$ scattering amplitudes, $\mathcal{F}_{123}^{C}$ is called the connected part of the $3 \to 3$ scattering amplitude.

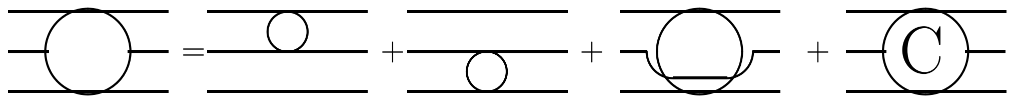

Fig. 1.

In the framework of single-time formalism in quantum field theory [3] we can use (4) to construct the $3 \to 3$ scattering amplitude T off energy shell with the same structure as (4)

$$T_{123} = T_{12} + T_{23} + T_{13} + T_{123}^{C}. \tag{5}$$

The three particle interaction quasipotential is related to the off-shell $3 \to 3$ scattering amplitude by the Lippmann-Schwinger type equation

$$T = V + VG_0T. \tag{6}$$

There is the same transformation between two particle interaction quasipotentials V_{ij} and off energy shell $2 \to 2$ scattering amplitudes

$$T_{ij} = V_{ij} + V_{ij}G_0T_{ij}. \tag{7}$$

It can be shown that in the relativistic quantum field theory the three particle interaction quasipotential has the following structure

$$V = V_{12} + V_{23} + V_{13} + V_0. \tag{8}$$

The quantity V_0 is called the three-body forces quasipotential. V_0 represents the defect of three particle interaction quasipotential over the sum of two particle interaction quasipotentials and describes the true three-body interactions.

The three-body forces scattering amplitude is related to the three-body forces quasipotential by the equation

$$T_0 = V_0 + V_0G_0T_0. \tag{9}$$

It should be stressed that the three-body forces appear as a result of consistent consideration of three-body problem in the framework of local quantum field theory.

Let us introduce the following useful notations

$$< p_1'p_2'p_3'|S-1|p_1p_2p_3 >= 2\pi\delta^4(\sum_{i=1}^{3} p_i' - \sum_{j=1}^{3} p_j)\mathcal{F}_{123}(s;\hat{e}',\hat{e}), \tag{10}$$

$$s = (\sum_{i=1}^{3} p_i')^2 = (\sum_{j=1}^{3} p_j)^2.$$

$\hat{e}', \hat{e} \in S_5$ are two unit vectors on five-dimensional sphere describing the configuration of three-body system in initial and final states (before and after scattering).

We will denote the quantity T_0 restricted on energy shell as

$$T_0 \mid_{on\, energy\, shell} = \mathcal{F}_0.$$

The unitarity condition for the quantity $\mathcal{F}_0$ with the account for the introduced notations can be written in form [9,10]

$$\begin{aligned} &Im\mathcal{F}_0(s;\hat{e}',\hat{e}) = \\ &= \ \pi A_3(s)\int d\Omega_5(\hat{e}'')\mathcal{F}_0(s;\hat{e}',\hat{e}'')\overset{*}{\mathcal{F}_0}(s;\hat{e},\hat{e}'') + H_0(s;\hat{e}',\hat{e}), \end{aligned} \tag{11}$$

$$Im\mathcal{F}_0(s;\hat{e}',\hat{e}) = \frac{1}{2i}\left[\mathcal{F}_0(s;\hat{e}',\hat{e}) - \overset{*}{\mathcal{F}_0}(s;\hat{e},\hat{e}')\right],$$

where

$$A_3(s) = \Gamma_3(s)/S_5,$$

$\Gamma_3(s)$ is the three-body phase-space volume, S_5 is the volume of unit five-dimensional sphere.

Let us introduce a special notation for the scalar product of two unit vectors $\hat{e}'$ and $\hat{e}$

$$\cos\omega = \hat{e}^{'} \cdot \hat{e}. \tag{12}$$

We will use the other notation for the three-body forces scattering amplitude as well

$$\mathcal{F}_0(s;\hat{e}',\hat{e}) = \mathcal{F}_0(s;\eta,\cos\omega),$$

where all other variables are denoted through η.

Now we are able to go to the formulation of our basic assumption about the analyticity properties for the three-body forces scattering amplitude.

2. Global analyticity of the three-body forces scattering amplitude

Let us formulate the basic assumption on the analytical properties of the three-body forces scattering amplitude [9,10].

We will assume that for physical values of the variable s and fixed values of η the amplitude $\mathcal{F}_0(s;\eta,\cos\omega)$ is an analytical function of the variable $\cos\omega$ in the ellipse $E_0(s)$ with the semi-major axis

$$z_0(s) = 1 + \frac{M_0^2}{2s} \tag{13}$$

and for any $\cos\omega \in E_0(s)$ and physical values of η it is polynomially bounded in the variable s. M_0 is some constant having mass dimensionality.

Such analyticity of the three-body forces amplitude was called a global one. The global analiticity may be considered as a direct generalization of the known analytical properties of two-body scattering amplitude strictly proved in the local quantum field theory.

At the same time the global analyticity gives us the generalized asymptotic bounds. For example the generalized asymptotic bound for $O(6)$-invariant three-body forces scattering amplitude looks like [9,10]

$$Im\,\mathcal{F}_0(s;...) \leq \text{Const}\, s^{3/2}(\frac{\ln s/s_0}{M_0})^5 = \text{Const}\, s^{3/2} R_0^5(s), \tag{14}$$

where $R_0(s)$ is the effective radius of the three-body forces

$$R_0(s) = \frac{\Lambda_0}{\sqrt{s}} = \frac{r_0}{M_0}\ln\frac{s}{s_0}, \tag{15}$$

r_0 is defined by the power of growth of the amplitude $\mathcal{F}_0$ at high energies [10], M_0 defines the semi-major axis of the global analyticity ellipse (13), Λ_0 is effective global orbital momentum.

It is well known that the Froissart asymptotic bound allows for its direct experimental verification because with the help of the optical theorem we can connect the imaginary part of $2 \to 2$ scattering amplitude with the experimentally measurable quantity which is the total cross section. So, if we want to have a possibility for the experimental verification of the generalized asymptotic bounds ($n \geq 3$) we have to establish a connection between the many-body forces scattering amplitudes and the experimentally measurable quantities. For this aim we have considered the problem of high energy particle scattering from deuteron and on this way we found the connection of three-body forces scattering amplitude with the experimentally measurable quantity which is the total cross section for scattering from deuteron.

I shall briefly sketch now the basic results of our analysis of the high energy particle scattering from deuteron.

3. Scattering from deuteron

The problem of scattering from two-body bound states was treated in works [7,8] with the help of dynamic equations obtained on the basis of single-time formalism in QFT [6]. As has been shown in [7,8], the total cross section in scattering from deuteron can be expressed by the formula

$$\sigma_d(s) = \sigma_p(s) + \sigma_n(s) - \delta\sigma(s), \tag{16}$$

where $\sigma_d, \sigma_p, \sigma_n$ are the total cross sections in scattering from deuteron, proton and neutron,

$$\delta\sigma(s) = \delta\sigma_G(s) + \delta\sigma_0(s), \tag{17}$$

$$\delta\sigma_G(s) = \frac{\sigma_p(s)\sigma_n(s)}{4\pi(R_d^2 + B_p(s) + B_n(s))} \equiv \frac{\sigma_p(s)\sigma_n(s)}{4\pi R_{eff}^2(s)}. \tag{18}$$

$B_N(s)$ is the slope of the forward diffraction peak in the elastic scattering from nucleon. $1/R_d^2$ is defined by the deuteron relativistic formfactor

$$\frac{1}{R_d^2} = \frac{q}{\pi}\int \frac{d\vec{\Delta}\Phi(\vec{\Delta})}{2\omega(\vec{q}+\vec{\Delta})}\delta\left[\omega(\vec{q}+\vec{\Delta}) - \omega(\vec{q})\right]. \tag{19}$$

$\delta\sigma_G$ is the Glauber correction or shadow effect. The Glauber shadow correction originates from elastic rescatterings of an incident particle on the nucleons inside the deuteron.

The quantity $\delta\sigma_0$ represents the contribution of the three-body forces to the total cross section in scattering from deuteron. The physical reason for the appearance of this quantity is directly connected with the inelastic interactions of incident particle with the nucleons of deuteron. Paper [8] provides for this quantity the following expression:

$$\delta\sigma_0(s) = -\frac{(2\pi)^3}{q}\int \frac{d\vec{\Delta}\Phi(\vec{\Delta})}{2E_p(\vec{\Delta}/2)2E_n(\vec{\Delta}/2)} Im\, R(s; -\frac{\vec{\Delta}}{2}, \frac{\vec{\Delta}}{2}, \vec{q}; \frac{\vec{\Delta}}{2}, -\frac{\vec{\Delta}}{2}, \vec{q}), \tag{20}$$

where q is the incident particle momentum in the lab system (rest frame of deuteron), $\Phi(\vec{\Delta})$ is the deuteron relativistic formfactor, normalized to unity at zero,

$$E_N(\vec{\Delta}) = \sqrt{\vec{\Delta}^2 + M_N^2} \quad N = p, n,$$

M_N is the nucleon mass. The function R is expressed via the amplitude of the three-body forces T_0 and the amplitudes of elastic scattering from the nucleons T_N by the relation

$$R = T_0 + \sum_{N=p,n} (T_0 G_0 T_N + T_N G_0 T_0). \tag{21}$$

In [7] the contribution of three-body forces to the scattering amplitude from deuteron was related to the processes of multiparticle production in the inelastic interactions of the incident particle with the nucleons of deuteron. This was done with the help of the unitarity equation. The character of the energy dependence of $\delta\sigma_0$ was shown to be governed by the energy behaviour of the corresponding inclusive cross sections.

On the other hand the expression for the quantity $\delta\sigma_0$ may be reduced to form [8]

$$\delta\sigma_0(s) = \frac{(2\pi)^3\chi(s)}{q}\int\frac{d\vec{\Delta}\Phi(\vec{\Delta})}{2E_p(\vec{\Delta}/2)2E_n(\vec{\Delta}/2)}Im\,\mathcal{F}_0(s;-\frac{\vec{\Delta}}{2},\frac{\vec{\Delta}}{2},\vec{q};\frac{\vec{\Delta}}{2},-\frac{\vec{\Delta}}{2},\vec{q}), \tag{22}$$

where the quantity $\chi(s)$ is defined via the total cross section $\sigma_N(s)$ and the slope of the forward diffraction peak $B_N(s)$ in elastic scattering from nucleon

$$\chi(s) = \frac{1}{4\pi}\frac{\sigma_p(s)}{B_p(s)} + \frac{1}{4\pi}\frac{\sigma_n(s)}{B_n(s)} - 1 \cong \frac{1}{2\pi}\frac{\sigma_N(s)}{B_N(s)} - 1, \tag{23}$$

$$s \cong 2qM_d.$$

If one assumes that in the region of high energies there takes place unitarity saturation of three-body forces, then using the asymptotic estimate (14) one can predict a possible character of the energy dependence for the quantity $\delta\sigma_0$. In particular, for 0(6)–invariant three-body forces amplitude we obtain [8]

$$\delta\sigma_0(s) = \frac{C_0\chi(s)\sqrt{s}/M_N}{R_d^3}(\frac{\ln s/s_0}{M_0})^5. \tag{24}$$

It should be remarked that in the derivation we assumed that the elastic scattering amplitudes from the nucleon were purely imaginary in the region of high energies and small momentum transfers. In the general case we would have [8]

$$\chi(s) = \frac{\sigma_N(s)}{2\pi B_N(s)}[1-\rho_0(s)\rho_N(s)] - 1, \tag{25}$$

where

$$\rho_0(s) = \frac{Re\mathcal{F}_0(s;\vec{0},\vec{0},\vec{q};\,\vec{0},\vec{0},\vec{q})}{Im\mathcal{F}_0(s;\vec{0},\vec{0},\vec{q};\,\vec{0},\vec{0},\vec{q})}, \quad \rho_N(s) = \frac{Re\mathcal{F}_N(s;t=0)}{Im\mathcal{F}_N(s;t=0)}. \tag{26}$$

From expression (24) for the correction $\delta\sigma_0$ it follows that

$$\delta\sigma_0 \sim \ln^2 s, \quad s\to\infty, \tag{27}$$

if and only if the asymptotic relation

$$\chi(s) \sim \frac{1}{\sqrt{s}\ln^3 s}, \quad s\to\infty \tag{28}$$

is valid. Therefore we immediately obtain the result mentioned in the introduction

$$\sigma_{tot}(s) = 2\pi B(s)(1+\chi). \tag{29}$$

In Table 1 we show the available experimental data for $p\bar{p}$ scattering extracted from database [5].

In the next section we will use a simple but "exactly solvable" model to find the cause of the bad agreement of the asymptotic relation (29) with the experimental data and write down a more precise formula.

4. Model calculation

For the more precise calculations it is convenient to make a phenomenological assumption on the structure of three-body forces. Let us deal with a model where the imaginary part of the three-body forces scattering amplitude has the form

$$Im\,\mathcal{F}_0(s;\vec{p}_1,\vec{p}_2,\vec{p}_3;\vec{q}_1,\vec{q}_2,\vec{q}_3) = f_0(s)\exp\left\{-\frac{R_0^2(s)}{4}\sum_{i=1}^{3}(\vec{p}_i-\vec{q}_i)^2\right\}, \tag{30}$$

where $f_0(s)$, $R_0(s)$ are free parameters which in general may depend on the total energy of three-body interaction. Note that the quantity $f_0(s)$ has the dimensionality $[R^2]$.

In case of unitarity saturation of the three-body forces we have from the generalized asymptotic theorems

$$f_0(s) \sim \text{Const}\, s^{3/2}(\frac{\ln s/s_0}{M_0})^5, \tag{31}$$

$$R_0(s) = \frac{r_0}{M_0}\ln s/s_0. \tag{32}$$

In the model all the integrals can be calculated exactly in the analytical form. As a result we obtain for the quantity $\delta\sigma_0$

$$\delta\sigma_0(s) = \frac{(2\pi)^6 f_0(s)}{sM_N}\left\{\frac{\sigma_N(s)}{2\pi[B_N(s)+R_0^2(s)-R_0^4(s)/4(R_0^2(s)+R_d^2)]}-1\right\}$$
$$\times\frac{1}{[2\pi(R_d^2+R_0^2(s))]^{3/2}}. \tag{33}$$

Obviously formula (24) follows from the exact result (33) in the region, where

$$R_0^2(s) \ll B_N(s) \ll R_d^2. \tag{34}$$

However from the physical statement for the problem of scattering from deuteron there are more preferable configurations for which the condition

$$R_0^2(s) \simeq B_N(s) \ll R_d^2 \tag{35}$$

is realized. In this case we obtain from the expression (33)

$$\delta\sigma_0(s) = \frac{C_0\tilde{\chi}(s)\sqrt{s}/M_N}{R_d^3}(\frac{\ln s/s_0}{M_0})^5, \tag{36}$$

where

$$\tilde{\chi}(s) = \frac{\sigma_N(s)}{2\pi[B_N(s)+R_0^2(s)]}-1. \tag{37}$$

It follows from the generalized asymptotic theorem (14) that the asymptotic behaviour (28) is also true for the $\tilde{\chi}(s)$

$$\tilde{\chi}(s) \sim \frac{1}{\sqrt{s}\ln^3 s}, \quad s\to\infty \tag{38}$$

However, instead of equation (29), we obtain a more precise asymptotic equation

$$\sigma_{tot}(s) = 2\pi[B(s) + R_0^2(s)](1 + \tilde{\chi}(s)). \tag{39}$$

In Table 1 we list the values for the quantity $R_0^2(s)$ extracted from the experimental data on $p\bar{p}$-scattering. These values are shown in Fig. 2 together with the experimental data for the slope of diffraction cone in $p\bar{p}$ elastic scattering.

Table 1. Total cross-sections and the slope of forward diffraction peak for $P\bar{P}$ scattering

$\sqrt{s}(GeV)$	$\sigma_{tot}(mb)$	$B(GeV^{-2})$	$\frac{1}{2\pi}\sigma_{tot}(GeV^{-2})$	$R_0^2(GeV^{-2})$
11.54	43.05 ± 0.16 [18]	11.60 ± 0.20 [19]	17.60	6.00
30.40	42.13 ± 0.57 [15]	12.70 ± 0.50 [15]	17.22	4.52
30.54	42.00 ± 0.50 [17]	11.37 ± 0.60 [17]	17.17	5.80
30.70	42.00 ± 0.50 [14]	12.60 ± 0.30 [14]	17.17	4.57
52.60	43.32 ± 0.34 [15]	13.03 ± 0.52 [15]	17.71	4.68
52.80	43.65 ± 0.41 [13]	13.36 ± 0.53 [13]	17.84	4.48
62.30	44.12 ± 0.39 [15]	13.47 ± 0.52 [15]	18.03	4.56
62.50	43.90 ± 0.60 [14]	13.10 ± 0.60 [14]	17.94	4.84
546	61.26 ± 0.93 [12]	15.28 ± 0.58 [11]	25.03	9.75
1800	72.80 ± 3.10 [16]	16.98 ± 0.25 [11]	29.76	12.78

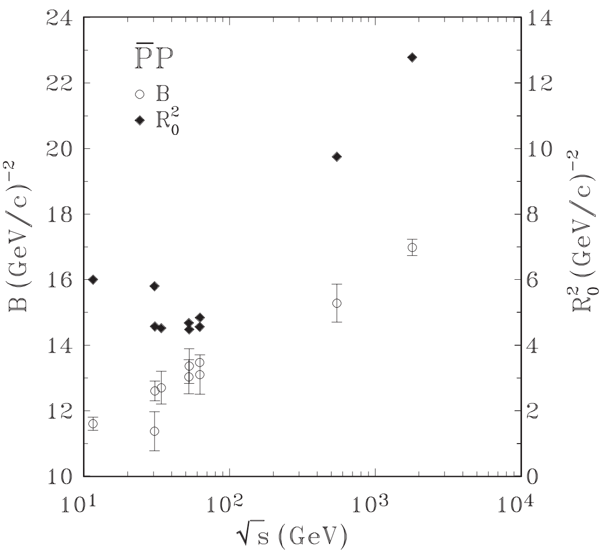

Fig. 2.

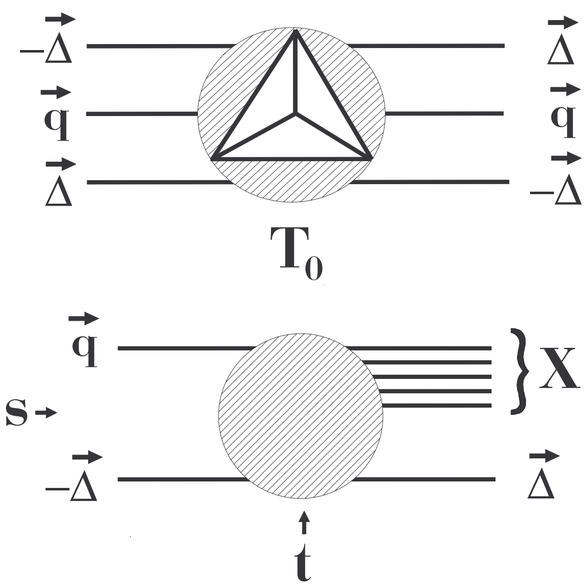

Fig. 3.

It is remarkable that the quantity R_0^2, which has the clear physical interpretation, can, at the same time, be connected with the experimentally measurable quantities. This important circumstance will be discussed again in the next section.

5. Three-body forces and diffractive dissociation processes

From the analysis of the problem of high-energy particle scattering from deuteron [8] the formula connecting one-particle inclusive cross section with the imaginary part of three-body forces scattering amplitude was derived. This formula looks like

$$2E_N(\vec{\Delta})\frac{d\sigma}{d\vec{\Delta}}(s,\vec{\Delta}) = (2\pi)^3\frac{M_N}{E_N(\vec{\Delta})}\frac{\chi(\bar{s})}{\bar{s}}Im\mathcal{F}_0(\bar{s};-\vec{\Delta},\vec{\Delta},\vec{q};\vec{\Delta},-\vec{\Delta},\vec{q}). \tag{40}$$

The configuration of particles momenta and kinematical variables are shown in Fig. 3. The variable $\bar{s}$ in the R.H.S. of Eq. (40) is related to the kinematical variables of one-particle inclusive reaction by the equation

$$\bar{s} = 2(s+M_N^2) - M_X^2, \tag{41}$$

$$t = -4\Delta^2.$$

The simple model for the three-body forces considered in the previous section gives us the following result for the one-particle inclusive cross section in the region of diffraction dissociation

$$\frac{s}{\pi}\frac{d\sigma}{dtdM_X^2} = (2\pi)^3\frac{\chi(\bar{s})f_0(\bar{s})}{\bar{s}}\exp\left[\frac{R_0^2(\bar{s})}{2}t\right] \tag{42}$$

$$\simeq C\sqrt{\bar{s}_0}\frac{(\ln\bar{s}/\bar{s}_0)^2}{M_0^5}\exp\left[\frac{R_0^2(\bar{s})}{2}t\right], \quad s\to\infty.$$

If we take the usual parameterization for one-particle inclusive cross section in the region of diffraction dissociation

$$\frac{s}{\pi}\frac{d\sigma}{dtdM_X^2} = A(s.M_X^2)\exp[b(s,M_X^2)t], \tag{43}$$

then we obtain for the quantities A and b

$$A(s,M_X^2) = C\sqrt{\bar{s}_0}\frac{(\ln\bar{s}/\bar{s}_0)^2}{M_0^5}, \tag{44}$$

$$b(s,M_X^2) = \frac{R_0^2(\bar{s})}{2}. \tag{45}$$

Eq. (45) shows that the effective radius of three-body forces is related to the slope of diffraction cone for inclusive diffraction dissociation processes in the same way as the effective radius of two-body forces is related to the slope of diffraction cone in elastic scattering processes.

If we take into account Eq. (41) then it follows from the Eq.(32) that the slope of diffraction cone for inclusive diffraction dissociation processes at fixed energy decreases with the growth of missing mass. This property agrees qualitatively with the experimentally observable picture.

Hence physically transparent notion of the effective radius of three-body forces, introduced previously as a pure mathematical object, connected with the global analyticity of three-body forces scattering amplitude, brings us to the tangible physical interpretation that helps us to create physically visual picture and representation for inclusive diffraction dissociation processes at the same level as we can understand and represent elastic scattering processes at high energies.

It should be noted that the asymptotic estimate (44) for the function A can be improved if we take into account the fact that in the R.H.S. of Eq. (40) we see the three-body forces scattering amplitude for the case when one particle moves in the forward direction but two other particles scatter in the backward direction in their common rest frame. In this case we have more precise asymptotic bounds for the three-body forces scattering amplitude. We will return to this fact in the future.

At last I'd like to draw your attention to the fact that relation (40) together with linear equation (9) for three-body forces scattering amplitude may be the basis of powerful dynamic apparatus for constructing the dynamical models of theoretical description of the inclusive reactions.

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