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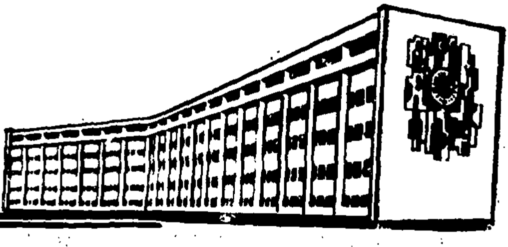

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ELASTIC HIGH-ENERGY PROTON SCATTERING ON ^{40}Ca WITH EXACT EXPRESSION FOR NUCLEON-NUCLEON AMPLITUDE AND FLUCTON CORRELATIONS

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Упругое высокоэнергетическое рассеяние протонов на ^{40}Ca с точным выражением для нуклон-нуклонной амплитуды и флуктонные корреляции

Дифференциальное сечение упругого рассеяния протонов с энергией 1 ГэВ на ^{40}Ca вычислено в рамках модели когерентных флуктуаций ядерной плотности (МКФЯП) и теории Глаубера-Ситенко. Показано, что: 1) использование точного нейконального выражения для двухчастичной амплитуды рассеяния, описывающей протон-протонные данные, ведет к удовлетворительному согласию с экспериментальными данными; 2) влияние флуктонных корреляций на дифференциальное сечение значительно, при этом использование реалистического зарядового распределения ведет к лучшему согласию результатов в МКФЯП с экспериментальными данными по сравнению с моделью независимых частиц.

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Elastic High-Energy Proton Scattering on ^{40}Ca With Exact Expression for Nucleon-Nucleon Amplitude and Flucton Correlations

The cross-section of the 1.04 GeV - proton elastic scattering from ^{40}Ca is calculated within the Glauber-Sitenko theoretical scheme using the coherent density fluctuation model (CDFM). It is shown that: 1) the use of exact noneikonal expression for the two-body scattering amplitude (which describes the p-p data) leads to a satisfactory agreement with the experimental data; 2) the influence of the flucton correlations on the cross-sections is considerable as the use of a realistic charge density distribution leads to a better agreement with the experimental data of the CDFM which is not the case of the independent-particle model.

1. INTRODUCTION

It is well known that the theory of Glauber-Sitenko (TGS) [1,2] provides a good basis to study the proton elastic and inelastic scattering on nuclei. Though different approximations have been used in the theory, e.g. eikonal (or high-energy), adiabatic ("frozen" nucleons) and dynamic (additivity of the nucleon shift-phases), the range of its validity proves to be quite large. It includes lower incident energies and larger scattering angles. The studies of the corrections to TGS show (e.g. [3]) that their total effect on the scattering cross-sections is small. In [4] an important conclusion is made that the high-order corrections to TGS have to be considered but after careful investigations of the nucleon-nucleon correlation effects. Though a large number of works are devoted to this problem, the effects of the correlations on the scattering, neglected in the independent-particle model (IPM), remain unclear. There exist different and often contradictory conclusions about the magnitude of the correlation effects. It concerns particularly the dynamic short correlations (SRC). For instance it is argued in [5] that the SRC effects are rather small. In [6] it is shown that they reach 10-12% of the total correlation effect (including center of mass- and Pauli-correlations). The calculations in other works (e.g. [7-12]) point out, however, that the SRC lead to a substantial increase in the cross-section maxima (for instance [8], with 24 and 35% for the first and second maxima in ^{40}Ca, with 9,23 and 33% in ^{58}Ni and with 15,23,30,37 and 43% in ^{208}Pb) and their influence cannot be neglected.

Another problem in the proton-nuclei scattering analysis is the poor knowledge of the proton-nucleon amplitude f_{pN}, particularly, at energies above 600 MeV which can cause uncertainties in the clculated cross-sections at larger transfer momentum. The attempts to obtain an exact axpression for the two-body elastic scattering amplitude in a wide range of angles are directed towards solving this problem. For instance, a suitable parametrization of the scattering amplitude which describes well the experimental elastic p-p scattering data (including data at large angles) is obtained in [13] on the basis of a noneikonal consideration.

In [14] the 1.04 GeV - proton elastic scattering from ^{40}Ca was studied in the framework of the coherent density fluctuation model (CDFM) [15] and the TGS. It was shown that the account of the specific for the CDFM type of correlations (so called "flucton correlations") leads to the results considerably different from those obtained in the IPM. The use of more realistic density distributions improves the agreement of the CDFM results with the experimental data in contrast to the case of the IPM. It was pointed out in [14], however, that the CDFM results do not fit well the experimental cross-section at angles larger than 18°. It was assumed that this is due to the uncertainties of the proton-nucleon amplitude. In the present work we extend our study from [14] of the flucton correlation effects using an exact expression of the proton-nucleon amplitude f_{pN} obtained from the noneikonal consideration in [13]. This gives opportunity for an important simultaneous analysis of the effects of a certain type of N-N correlations and of the use of noneikonal two-body amplitude (which describes the experimental proton-proton scattering data) on the proton-nuclei scattering cross-section. In addition, the use of such amplitude throws light upon the question for the behaviour of the noneikonal proton-nuclei scattering amplitude.

II. BASIC RELATIONS FOR THE PROTON-NUCLEI SCATTERING AMPLITUDE

It has been shown [14] that in the CDFM the Glauber-Sitenko amplitude for the proton elastic scattering on nuclei can be presented in the form

$$F_{oo}(q)=\int_0^\infty |f(x)|^2\, F_x(q)\, dx. \tag{1}$$

$F_x(q)$ is the amplitude of the proton scattering from a system of A nucleons uniformly distributed in a sphere with a radius X (so called "flucton"):

$$F_x(q)=f_p(q)+ik\int_0^\infty J_0(qb)\left\{\exp\left[i\chi_p(b)\right]-G_A(x,b)\exp\left[i\chi_f(x,b)\right]\right\}b\,db. \tag{2}$$

In (2) $\vec{q}$ is the transfer momentum and $\hbar\vec{k}$ is the momentum of the incoming proton. $f_p(q)$ is the Coulomb scattering amplitude for a point charge Z :

$$f_p(q) = -\left(\frac{2\alpha k}{q^2}\right) \exp\left[2i\arg\Gamma(1+i\alpha) - 2i\alpha\ln\left(\frac{q}{2}\right)\right] \tag{3}$$

and the corresponding point Coulomb phase is

$$\chi_p(b) = 2\alpha \ln b \tag{4}$$

($\alpha = \frac{Ze^2}{\hbar V}$, V is the velocity of the incoming proton in the laboratory system). $\chi_\rho(x,b)$ is the Coulomb phase for the proton scattering on a flucton with radius x :

$$\chi_\rho(x,b) = \chi_p(b) + 2\alpha\int_0^\infty J_0(qb)\left[1 - S(x,b)\right]\frac{dq}{q} = \tag{5a}$$

$$= \chi_p(b) + 2\alpha\,\theta(x-b)\left\{\ln\left[\frac{x}{b} + \sqrt{\left(\frac{x}{b}\right)^2 - 1}\right] + \frac{\sqrt{\left(\frac{x}{b}\right)^2 - 1}}{3\left(\frac{x}{b}\right)^3}\left[1 - 4\left(\frac{x}{b}\right)^2\right]\right\}. \tag{5b}$$

In (5a)

$$S(x,q) = 3\left[\sin qx - qx\cos qx\right] / (qx)^3 \tag{6}$$

is the flucton formfactor. The nuclear part of the amplitude (2) is

$$G_A(x,b) = \left\{1 - \left[G(x,b) + \Delta G(x,b)\right]\right\}^A, \tag{7}$$

where

$$G(x,b) = \frac{1}{ik}\int_0^\infty J_0(qb)\, f_{pN}(q)\, S(x,q)\, q\, dq \tag{8}$$

and the part

$$\Delta G(x,b) = \frac{3(A-1)b^2\left[G(x,b)\right]^2}{2(A-2)\langle r^2\rangle_x} \tag{9}$$

takes into account the center of mass correlations [16]. $f_{pN}(q)$ is the proton-nucleon scattering amplitude and $\langle r^2\rangle_x = 0.6x^2$ is the r.m.s. radius of the flucton of a size x .

In (1) the proton-nucleus elastic scattering amplitude is presented as a linear combination of proton-flucton amplitudes $F_x(q)$ weighted by the function $|f(x)|^2$. It is shown [14, 15] that for monotonically decreasing density distribution the weight function $|f(x)|^2$ can be expressed by

$$|f(x)|^2=-\frac{1}{\rho_0(x)}\,\frac{d\rho}{dr}\Big|_{r=x}\,, \tag{10}$$

where $\rho_0(x)=3A/4\pi x^3$. In order to determine the function $|f(x)|^2$ from (10) (under the assumption $\rho=2\rho_p$) one needs the nucleon proton density $\rho_p(\vec r)$ corresponding to the nucleon charge density $\rho_{ch}(\vec r)$:

$$\rho_{ch}(\vec r)=\int\rho_{cp}(\vec r\,')\,\rho_p(\vec r-\vec r\,')\,d\vec r\,'. \tag{11}$$

In (11) $\rho_{cp}(\vec r)$ is the charge distribution of the proton. Finally one obtains the weight function $|f(x)|^2$ in the form

$$|f(x)|^2=\frac{2x^3}{3\pi}\int_0^\infty j_1(qx)\,S_{ch}(q)\,S_{cp}^{-1}(q)\,q^3dq\,. \tag{12}$$

where $S_{ch}(q)$ and $S_{cp}(q)$ are formfactors corresponding to the nuclear chrge density ρ_{ch} and to the charge density of the proton ρ_{cp} , respectively. $j_1(qx)$ is the spherical Bessel function.

We note that in the CDFM (as shown in [14,15]) the flucton correlations are related to the homogeneous distribution of the nucleons in the intermediate states corresponding to configurations in which all A nucleons are confined in a finite volume (spheres with radius x). Some of these configurations have a high value of the density $\rho_0\sim 1/x^3$ at small x so that the nucleons are close to each other and short-range components of the nucleon-nucleon forces can be operative.

In the case of the IPM the form of the Glauber-Sitenko amplitude [16] coincides with (2), but:

1) the flucton formfactor $S(x,q)$ in the Coulomb phase (5a) is replaced by the charge formfactor $S_{ch}(q)$;

2) in the nuclear part (Eqs.(7)-(9)) the formfactor $S(x,q)$ is replaced by the expression $S_{ch}(q)\,S_{cp}^{-1}(q)$;

3) the r.m.s. radius of the nucleus is used instead of the flucton r.m.s. one in (9).

III. PROTON-NUCLEON SCATTERING AMPLITUDE

It has been pointed out in [14] that the CDFM results for the 1.04 GeV - proton elastic scattering from ^{40}Ca do not fit exactly the experimental data, mainly at angles greater than 18°.

It was argued that this might be related to many different factors. One of them is the form of the proton-nucleon amplitude $f_{pN}(q)$ used in the calculations:

$$f_{pN}(q)=\frac{k\sigma}{4\pi}(i+\varepsilon)\exp\left(-\beta q^{2}/2\right) \tag{13}$$

and the uncertainties of its parameters.

As mentioned in the Introduction this problem is connected with the necessity to find an exact expression for the two-body elastic scattering amplitude which describes the experimental scattering data. Moreover , it concerns the question for the noneikonal corrections to the proton-nucleus scattering amplitude. For this purpose, it is of interest to calculate the 1.04 GeV - proton elastic scattering cross-section in the framework of CDFM (Eqs.(1)-(12)) using the exact expression for the proton-nucleon scattering amplitude. We use in our calculations the two-body amplitude obtained in [13] on the nasis of the Sugar-Blankenbecler eikonal expansion [17] for the T-matrix:

$$T=\tilde{T}G_{o}\Delta\tilde{G}_{o}T+\tilde{T} \tag{14}$$

with

$$\Delta=\tilde{G}_{o}^{-1}-G_{o}^{-1}, \tag{15}$$

where $\tilde{T}$ is the eikonal scattering matrix and G_o and $\tilde{G}_o$ are free exact and eikonal Green functions, respectively. Using the operator identity

$$G_{o}\Delta\tilde{G}_{o}\equiv G_{o}-\tilde{G}_{o} \tag{16}$$

an infinite series can be obtained [13] from Eq.(14):

$$T=\tilde{T}+\tilde{T}(G_{o}-\tilde{G}_{o})\tilde{T}+\tilde{T}(G_{o}-\tilde{G}_{o})\tilde{T}(G_{o}-\tilde{G}_{o})\tilde{T}+\dots \tag{17}$$

The evaluation of the terms in (17) leads to the following expression for the proton-proton scattering amplitude [13]

$$f_{pN}(q)=\frac{i\sigma k}{4\pi}\sum_{n=0}^{\infty}A_{n+1}\left(\frac{\sigma}{4\pi\beta}\right)^{n}\frac{(1-i\varepsilon)^{n+1}}{n+1}\exp\left[-\frac{\beta q^{2}}{2(n+1)}\right]. \tag{18}$$

The parameters σ,ε and β in (18) are chosen under the conditions that: 1) the optical theorem be valid; 2) the ratio $Re f(0)/Im f(0)$ be equal to the experimental value and 3) the experimental elastic p-p cross-section data be correctly reproduced.

In (18) A_n are numerical coefficients. It can be shown that they satisfy the following recurrent relation:

$$A_{n+1} = \frac{A_1}{n(n+1)} + \frac{A_2}{(n-1)n} + \frac{A_3}{(n-2)(n-1)} + \dots + \frac{A_n}{1\cdot 2}$$

with $A_1 = 1$.

The equation (18) is an exact noneikonal expression for the proton-proton scattering amplitude in which the Fresnel corrections (the nonstraight line propagation of the incoming particle) are taken into account. The amplitude (18) describes correctly the experimental data for the elastic proton-proton scattering in the region $0° < \theta < 90°$ [18,19]. The study of the sensitivity of the calculated proton-proton cross-section with respect to the number of terms in (18) shows that at $n \geqslant 50$ the results are practically unchanged. For this reason the proton - ^{40}Ca cross-section calculations are performed with n=50 .

The use of (18) in the CDFM calculations of the proton - ^{40}Ca elastic cross-section is a test for the applicability of this amplitude to describe the scattering by complex nuclei.

IY. NUMERICAL RESULTS AND DISCUSSION

The elastic scattering cross-section of 1.04 GeV - protons on ^{40}Ca have been calculated using the relations (1)-(12) and the two-body amplitude (18). The choice of ^{40}Ca is related to the small center of mass effects and the negligible difference between the proton and neutron distributions for this nucleus.

The realistic charge density $\rho_{ch}(\vec{r})$ obtained by means of model-independent analysis of experimental data on electron scattering and muonic atoms (type I from [20]) is used in Eq.(11). The dipole formula

$$S_{cp}(q) = (1 + q^2/\lambda)^{-2} \qquad (19)$$

with $\lambda = 0.71\ (\mathrm{GeV/c})^2$ for the formfactor $S_{cp}(q)$ is used in Eq.(12). This choice leads to the integral convergence in (12) in our case of exponential asymptotic of the charge formfactor $S_{ch}(q)$.

In the CDFM calculations we find a set of parameter values for σ, β and ε in (18):

$$\sigma = 3.2128 \text{ fm}^2, \quad \beta = 0.30 \text{ fm}^2, \quad \varepsilon = -0.18 \qquad (20)$$

which gives the optimal fit both to the p - ^{40}Ca cross-section experimental data and to the experimental elastic proton-proton cross-section data. These values satisfy the optical theorem (with $\sigma_{tot} = 4.4$ fm^2) and give the ratio $\mathrm{Re} f(0)/\mathrm{Im} f(0) = -0.3426$ which is in accordance with the experimental data (within their uncertainties).

In Fig.1 we present the CDFM and IPM results obtained using the amplitude (18) with parameter values (20) in a comparison with the experimental data [16] for the 1.04 GeV proton - ^{40}Ca elastic cross-section. The numerical results confirm the conclusion from [14] that the influence of the flucton correlations is significant - there is a considerable difference between the IPM and CDFM results. As in [14] the use of a realistic density [20] leads to a disagreement in the case of IPM and to a better agreement of the CDFM results with the data.

In Fig.2 the comparison of the CDFM results obtained using the amplitude $f_{pN}(q)$ from (13) (with $\sigma = 4.4$ fm^2, $\beta = 0.24$ fm^2, $\varepsilon = -0.28$) [14] and using $f_{pN}(q)$ from (18) with parameter values (20) is given. It can be seen the better agreement of the results using the amplitude (18) with the experimental data at angles greater than 18°. In Fig.3 the same comparison is given for the IPM results. The comparison of the proton-proton elastic cross-section calculated using (18) and (20) with the experimental data [18,19] is presented in Fig.4. In the calculations we assume that the values of the parameter set σ, β, ε for the proton-neutron amplitude are the same as for the proton-proton amplitude (20). In contrast to the CDFM case, our calculations in the framework of the IPM showed that it is impossible to find a set of parameter values for σ, β and ε in (18) which gives a correct fit simultaneously to the p - ^{40}Ca cross-section data and to the p-p elastic cross-section data. In particular, the IPM calculations for the p - ^{40}Ca cross-section give the last minimum in the region of $\theta \simeq 17°$ for every reasonable parameter set which describes the p-p data while the experimental minimum is at $\theta \simeq 18°$.

Summarizing we conclude that:

1) the use of the noneikonal two-body amplitude (18) (accounting for the Fresnel corrections and describing the p-p data) in the CDFM calculations of the p - ^{40}Ca elastic scattering cross-section leads to a satisfactory agreement with the experimental data. In comparison with the use of $f_{pN}(q)$ (13) the agreement is better at angles $\theta \gtrsim 18°$.

2) The present calculations of the p - ^{40}Ca elastic scattering cross-section with the two-body amplitude (18) confirm the conclusion made in [14] (where $f_{pN}(q)$ given by (13) is used) that the influence of the flucton correlations is significant.

3) The use of a realistic density distribution enables the CDFM results for the p - ^{40}Ca cross-section to agree better with the data than the independent-particle model calculations.

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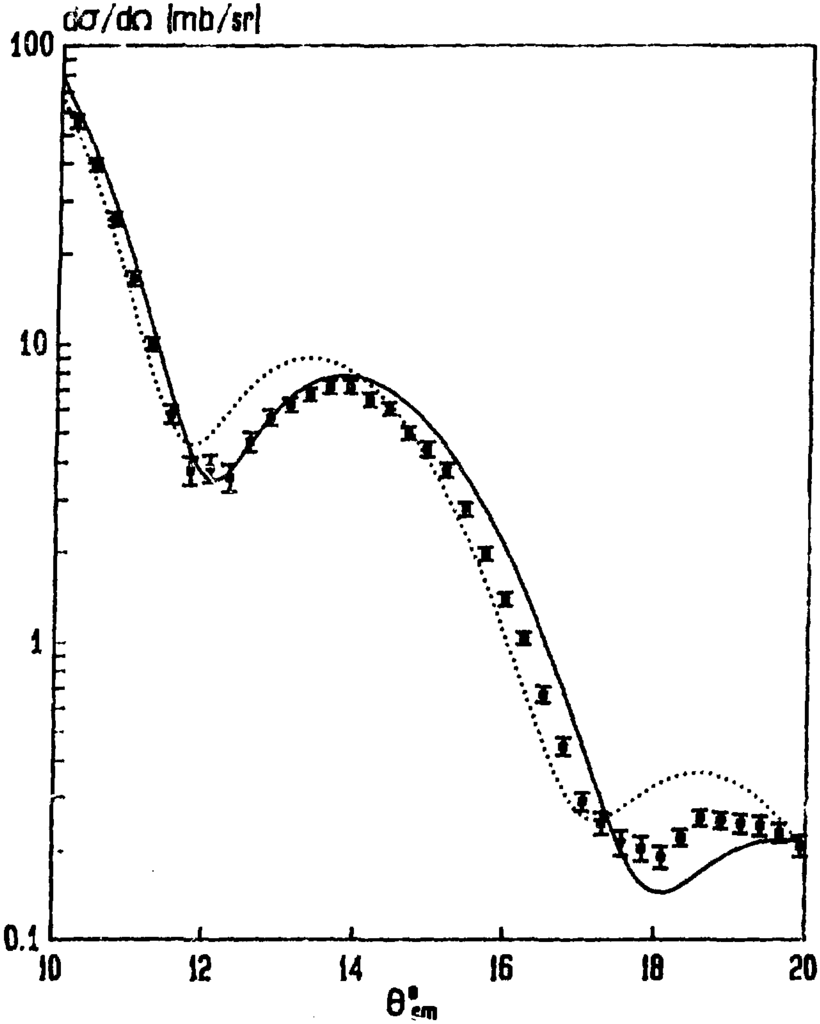

Fig.1. The cross-section of the elastic 1.04 GeV - proton scattering from ^{40}Ca calculated using two-body amplitude $f_{pN}(q)$ from (18),(20).—— in the coherent density fluctuation model (CDFM); .... in the independent-particle model (IPM). The experimental data are taken from [16].

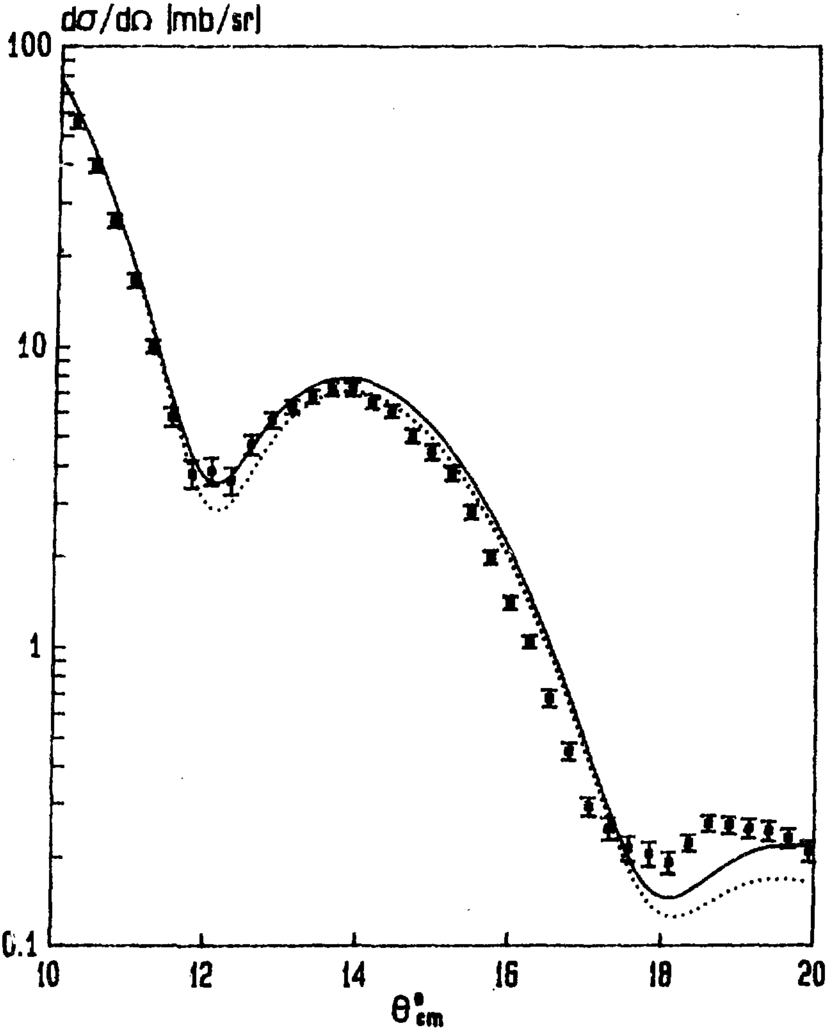

Fig.2. The CDFM results for the elastic 1.04 GeV proton - ^{40}Ca cross-section. —— using $f_{pN}(q)$ from (18),(20); .... using $f_{pN}(q)$ from (13) with σ = 4.4 fm^2, β = 0.24 fm^2, ε =-0.28; the experimental data as in Fig.1.

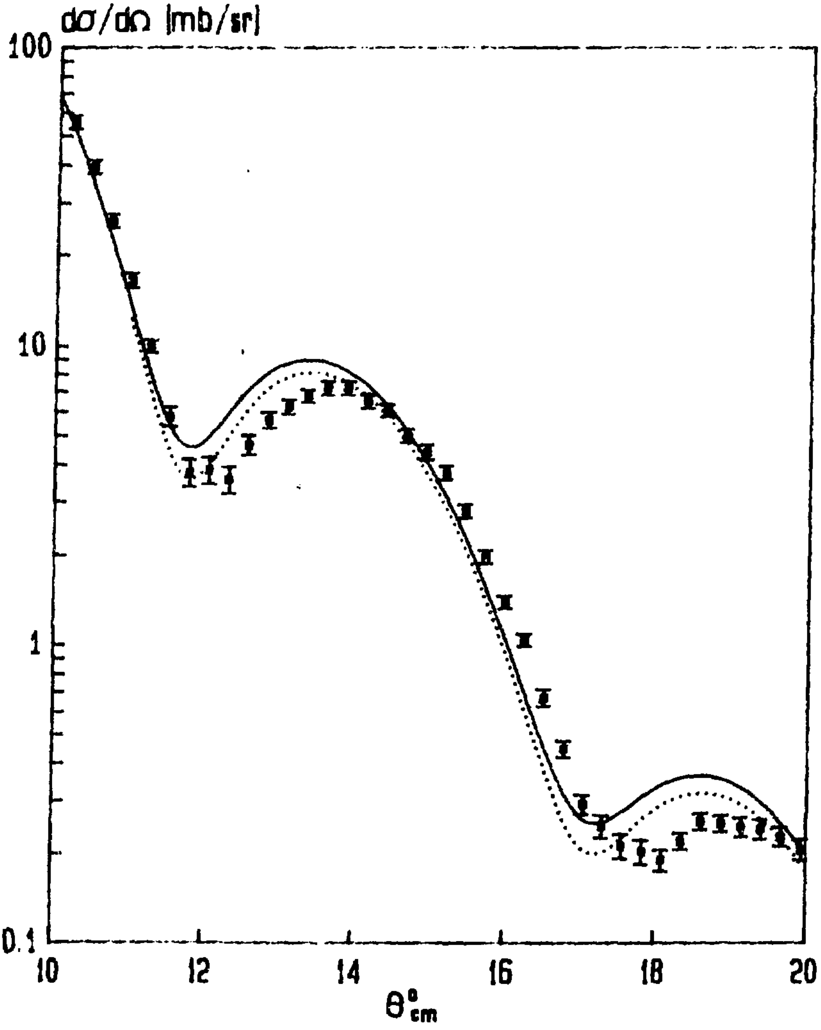

Fig.3. The IPM results for the elastic 1.04 GeV proton - ^{40}Ca cross-section. —— using $f_{pN}(q)$ from (18),(20); .... using $f_{pN}(q)$ from (13) with σ = 4.4 fm^2, β = = 0.24 fm^2, ε = -0.28); the experimental data as in Fig.1.

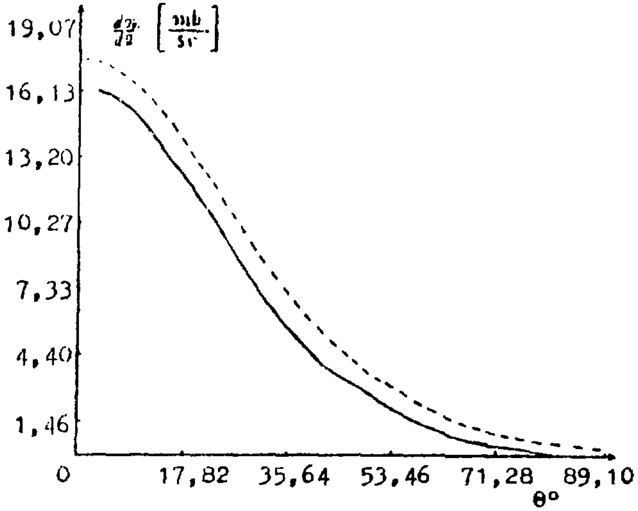

Fig.4. The cross-section of the elastic proton-proton scattering. ---- experimental data [18,19]; —— calculated using $f_{pp}(q)$ from (18),(20).

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Упругое высокоэнергетическое рассеяние протонов на ^{40}Ca с точным выражением для нуклон-нуклонной амплитуды и флуктонные корреляции

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