STATE RESEARCH CENTER OF RUSSIA

INSTITUTE FOR HIGH ENERGY PHYSICS

IHEP 97-6

A.A. Arkhipov, P.M. Nadolsky

EFFECTIVE RADIUS OF THREE-NUCLEON FORCES AND $p\bar{p}$ SINGLE DIFFRACTION DISSOCIATION AT HIGH ENERGIES

Protvino 1997

UDK 539.1.01 M–24

Abstract

Arkhipov A.A., Nadolsky P.M. Effective Radius of Three-Nucleon Forces and $p\bar{p}$ Single Diffraction Dissociation at High Energies: IHEP Preprint 97-6. – Protvino, 1997. – p. 8, figs. 2, tables 3, refs.: 22.

Effective radius of three-nucleon forces is extracted from the experimental data. The obtained values for the radius are compared with the data on the $p\bar{p}$ single diffraction dissociation cross-sections at high energies.

PACS number(s): 11.80.-m, 13.85.-t, 21.30.+y.

Keywords: $p\bar{p}$ inclusive reactions, diffraction dissociation, elastic scattering, total cross-sections, slope of diffraction cone, numeric calculations, fit to the data, interpretation of experiments.

Аннотация

Архипов А.А., Надольский П.М. Эффективный радиус трехнуклонных сил и диффракционная диссоциация $\bar{p}p \to \bar{p}X$ при высоких энергиях: Препринт ИФВЭ 97-6. – Протвино, 1997. – 8 с., 2 рис., 3 табл., библиогр.: 22.

Из экспериментальных данных по полным сечениям и наклону дифракционного конуса в $p\bar{p}$-рассеянии извлечен эффективный радиус трехнуклонных сил. Проведено сравнение полученных значений для эффективного радиуса с экспериментальными данными для сечений диффракционной диассоциации $\bar{p}p \to \bar{p}X$ при высоких энергиях.

© State Research Center of Russia
Institute for High Energy Physics, 1997

Introduction

The last experimental measurement of $p\bar{p}$ single diffraction dissociation at c.m.s. energies $\sqrt{s} = 546$ and $1800\ GeV$, carried out by the CDF group at the Fermilab Tevatron collider, has shown that the popular model of supercritical Pomeron does not describe the existing experimental data.

The statement, made in [1], is as follows: the value of $\sigma_{SD}^{p\bar{p}} = (7.89 \pm 0.33)\ mb$, measured at $\sqrt{s} = 546\ GeV$, is extrapolated by the supercritical Pomeron model to $\sigma_{SD}^{p\bar{p}} = (13.9 \pm 0.9)\ mb$ at $\sqrt{s} = 1800\ GeV$, while the measured value at this energy is equal to $\sigma_{SD}^{p\bar{p}} = (9.45 \pm 0.44)\ mb$. The ratio of the measured $\sigma_{SD}^{p\bar{p}}$ to that obtained by extrapolation is

$$\frac{\sigma_{SD}^{p\bar{p}}(experimental)}{\sigma_{SD}^{p\bar{p}}(extrapolation)}(\sqrt{s} = 1800\ GeV) = 0.68 \pm 0.05. \qquad (1)$$

Besides that, at $\sqrt{s} = 20\ GeV$ the experimental $\sigma_{SD}^{p\bar{p}} = (4.9 \pm 0.55)\ mb$ is 4.5 times larger than the value $\sigma_{SD}^{p\bar{p}} = (1.1 \pm 0.17)\ mb$, obtained by the extrapolation of the measured value of $\sigma_{SD}^{p\bar{p}}$ at $\sqrt{s} = 546\ GeV$ down to $\sqrt{s} = 20\ GeV$ with the help of the supercritical Pomeron model.

The emerging situation can be considered as a supercrisis for the supercritical Pomeron model. Obviously, the foundations of this model require further theoretical study and the construction of newer, more general phenomenological framework, which would enable us to remove the discrepancy between the model predictions and experiment. In relation to this, one should note paper [2], where an attempt to save the supercritical Pomeron model has been undertaken.

Another approach to the dynamical description of one-particle inclusive reactions has been proposed in [3]. The consideration, presented in this paper, revealed several fundamental properties of one-particle inclusive cross-sections in the region of diffraction dissociation. In particular, it has been shown that the slope of the diffraction cone in $p\bar{p}$ single diffraction dissociation is related to the effective radius of three-nucleon forces in the same way as the slope of the diffraction cone in elastic $p\bar{p}$ scattering is related to the effective radius of two-nucleon forces. It was also demonstrated that the effective radii of two- and three-nucleon forces, which were the characteristics of elastic and inelastic interactions of two nucleons, define the structure of the $p\bar{p}$ total cross-sections in a simple and physically transparent form.

In the present work we performed a more detailed analysis of the experimental data on $p\bar{p}$ total cross-sections and the slope of the diffraction cone in elastic $p\bar{p}$ scattering. This allowed us to extract the effective radius of three-nucleon forces. We also presented a semiquantitative comparison of the extracted values for the effective radius of three-nucleon forces to the experimental data on $p\bar{p}$ single diffraction dissociation cross-sections at high energies.

1. Fit to the data on the $p\bar{p}$ total cross-sections

As a first step, we made a weighted fit to the experimental data on the $p\bar{p}$ total cross-sections, obtained from COMPAS-PPDS database [1]. The values, which were used, are listed in Table 1.

Table 1. The $p\bar{p}$ total cross-sections(statistical and systematic errors added in quadrature).

$\sqrt{s}$ (GeV)	σ_{tot} (mb)	$\delta\sigma_{stat}$ (mb)	$\delta\sigma_{sys}$ (mb)	$\sigma_{tot}/2\pi$ (GeV^{-2})
9.78	43.10 ± 0.94	0.80	0.50	17.62 ± 0.39
11.54	43.05 ± 0.12	0.06	0.10	17.60 ± 0.05
13.76	42.12 ± 0.13	0.08	0.10	17.22 ± 0.05
13.86	42.33 ± 0.14	0.14	0.00	17.30 ± 0.06
15.06	41.70 ± 0.18	0.15	0.10	17.04 ± 0.07
16.83	41.79 ± 0.20	0.17	0.10	17.08 ± 0.08
17.91	41.69 ± 0.18	0.15	0.10	17.04 ± 0.07
19.42	41.51 ± 0.15	0.15	0.00	16.97 ± 0.06
19.42	41.44 ± 0.21	0.18	0.10	16.94 ± 0.08
21.26	41.90 ± 0.20	0.20	0.00	17.13 ± 0.08
22.96	41.91 ± 0.21	0.21	0.00	17.13 ± 0.09
30.40	42.13 ± 0.64	0.57	0.30	17.22 ± 0.26
30.63	42.80 ± 0.35	0.35	0.00	17.49 ± 0.14
52.59	43.32 ± 0.35	0.34	0.10	17.71 ± 0.15
52.82	44.71 ± 0.46	0.46	0.00	18.28 ± 0.19
62.29	44.12 ± 0.44	0.39	0.20	18.03 ± 0.18
62.71	45.14 ± 0.38	0.38	0.00	18.45 ± 0.16
540	66.80 ± 7.13	5.90	4.00	27.30 ± 2.91
540	66.00 ± 8.60	7.00	5.00	26.98 ± 3.52
546	61.26 ± 0.93	0.93	0.00	25.04 ± 0.38
546	61.90 ± 1.50	1.50	0.00	25.30 ± 0.61
899	65.30 ± 2.40	0.70	2.30	26.69 ± 0.98
1800	80.03 ± 2.24	2.24	0.00	32.71 ± 0.92
1800	72.80 ± 3.10	3.10	0.00	29.76 ± 1.28

[1] The COMPAS database (named Particle Physics Data System - PPDS) can be reached via Internet at http://www.ihep.su, or at its mirror http://muse.lbl.gov:8001/ppds.html

The reduced quantities $\sigma_{tot}^{p\bar{p}}/2\pi$ in GeV^{-2} were fitted with the function of the form

$$\sigma_{tot}^{p\bar{p}}/2\pi = a_0 + a_2 \ln^2(\sqrt{s}/\sqrt{s_0}), \tag{2}$$

where a_0, a_2, $\sqrt{s_0}$ are free parameters. We accounted for the experimental errors δx_i by fitting to the experimental points with the weight

$$w_i = \frac{1}{(\delta x_i)^2}. \tag{3}$$

Our fit yielded

$$a_0 = (17.15 \pm 0.06)\ GeV^{-2} \tag{4}$$
$$a_2 = (0.70 \pm 0.04)\ GeV^{-2} \tag{5}$$
$$\sqrt{s_0} = (18.99 \pm 1.95)\ GeV. \tag{6}$$

The fit result is shown in Fig.1.

The quality of the fit can be checked by the extrapolation of formula (2) to the higher energies:

$$\sigma_{tot}^{p\bar{p}}(\sqrt{s} = 16\ TeV) = (119.67 \pm 4.60)\ mb, \tag{7}$$
$$\sigma_{tot}^{p\bar{p}}(\sqrt{s} = 30\ TeV) = (134.85 \pm 5.46)\ mb. \tag{8}$$

These values are consistent with the recent cosmic rays results from Akeno Observatory [4],

$$\sigma_{tot}^{pp}(\sqrt{s} = 30\ TeV) = (120 \pm 15)\ mb. \tag{9}$$

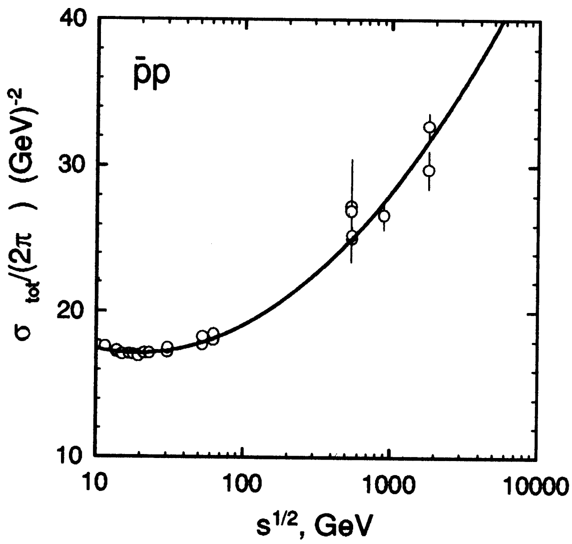

Fig. 1.

2. Fit to the data on the slope of diffraction cone in elastic $p\bar{p}$ scattering

Compared with the data on the $p\bar{p}$ total cross-sections, the experimental data on the slope of diffraction cone in elastic $p\bar{p}$ scattering is certainly less comprehensive. Therefore, at the first stage we fitted the experimental data on the differential cross-sections in elastic $p\bar{p}$ scattering from Ref. [5]; from this fit, we extracted the values of the slope of diffraction cone at five different energies. As a fitting function, we used the linear exponent

$$\frac{d\sigma}{dt} = A \exp(Bt), \tag{10}$$

where A and B were considered as free fit parameters. The obtained fit parameters and the values of χ^2 are listed in Table 2.

Table 2. Fitted parameters. $d\sigma/dt = Aexp(Bt)(mb/GeV^2)$, $(0.0375 \leq -t \leq 0.4(GeV^2))$

$\sqrt{s}$ (GeV)	lnA	B (GeV^{-2})	$\chi^2/d.o.f.$
9.78	4.552 ± 0.016	11.66 ± 0.13	0.86
11.54	4.428 ± 0.011	11.67 ± 0.10	0.41
13.76	4.493 ± 0.037	11.47 ± 0.24	0.54
16.26	4.346 ± 0.052	10.74 ± 0.35	0.86
18.17	4.30 ± 0.042	11.06 ± 0.24	0.88

Table 3. Data on the slope at $t \simeq 0$ in $p\bar{p}$ scattering (statistical and systematic errors added in quadrature).

$\sqrt{s}$ (GeV)	B (GeV^{-2})	References
9.78	11.66 ± 0.13	[5]
11.54	11.67 ± 0.10	[5]
11.54	11.6 ± 0.2	[5]
13.76	11.47 ± 0.24	[5]
13.76	11.4 ± 0.6	[22]
13.76	13.2 ± 1.2	[7]
16.26	10.74 ± 0.35	[5]
18.17	11.06 ± 0.24	[5]
19.42	17.0 ± 3.6	[7]
24.3	12.3 ± 0.5	[15]
24.3	12.51 ± 0.11	[15]
30.5	11.37 ± 0.60	[13]
52.6	13.03 ± 0.52	[18]
52.8	13.36 ± 0.53	[9]
52.8	13.6 ± 2.2	[6]
52.8	13.92 ± 0.43	[11]
62.3	13.47 ± 0.52	[18]
540	17.1 ± 1.0	[10]
540	17.2 ± 1.0	[8]
540	17.6 ± 1.0	[12]
541	15.52 ± 0.07	[19]
546	15.28 ± 0.59	[21]
546	15.3 ± 0.3	[12]
546	15.35 ± 0.19	[21]
1800	16.3 ± 0.3	[16]
1800	16.3 ± 0.5	[20]
1800	16.98 ± 0.25	[21]
1800	16.99 ± 0.47	[17]
1800	17.2 ± 1.3	[14]

The obtained five values of the slope, together with the other experimental values from COMPAS database, were used to build a weighted fit of the slope as a function of energy. Table 3 shows the list of the fitted data. The following parameterization of the slope was assumed:

$$B = b_0 + b_2 \ln^2(\sqrt{s}/\sqrt{s_0}). \tag{11}$$

The value $\sqrt{s_0}$ has been fixed by (6) from the fit to the $p\bar{p}$ total cross-sections. Parameterization (11) is suggested by the asymptotic theorems of the axiomatic quantum field theory. Our fit yielded

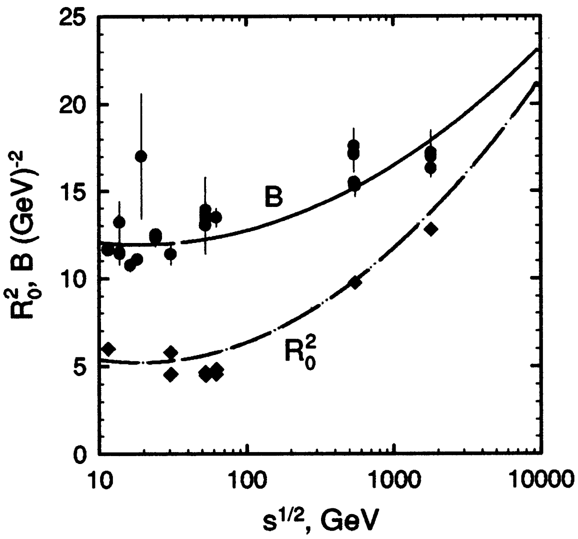

Fig. 2.

$$b_0 = (11.93 \pm 0.15)\ GeV^{-2}, \tag{12}$$
$$b_2 = (0.29 \pm 0.02)\ GeV^{-2}. \tag{13}$$

The fitting curve is shown in Fig.2.

3. The effective radius of three-nucleon forces and $p\bar{p}$ single diffraction dissociation cross-sections

In paper [3] the asymptotic relation between the slope of diffraction peak in elastic $p\bar{p}$ scattering and the $p\bar{p}$ total cross-sections has been obtained. The relation looks like

$$\sigma_{tot}(s) = 2\pi\ [B(s) + R_0^2(s)]. \tag{14}$$

The quantity $R_0^2(s)$ in the R.H.S. of (14) is responsible for the inelastic processes in $p\bar{p}$ interactions. It has a physically transparent notion of the effective radius of three-nucleon forces.

We can use (14) to extract the quantity $R_0^2(s)$ from the experimental data on the $p\bar{p}$ total cross-sections and the slope of diffraction cone in elastic $p\bar{p}$ scattering. Using the fits (2,11), we obtain

$$R_0^2(s) = [(5.22 \pm 0.21) + (0.41 \pm 0.06)\ln^2(\sqrt{s}/\sqrt{s_0})]\ GeV^{-2}, \quad \sqrt{s_0} = (18.99 \pm 1.95)\ GeV. \tag{15}$$

Function (15) is plotted in the same Fig. 2, together with the fit to $B(s)$. Fig. 2 also shows the points for $R_0^2(s)$ obtained earlier [3] .

It is a remarkable fact that the quantity $R_0^2(s)$ defines the slope of the diffraction cone in the $p\bar{p}$ single diffraction dissociation inclusive cross-sections. It has been shown in [3] that in the region of diffraction dissociation one-particle inclusive cross-sections can asymptotically be represented in the form

$$\frac{s}{\pi}\frac{d\sigma}{dtdM_X^2} = A(s.M_X^2)\exp[b(s, M_X^2)t], \tag{16}$$

where

$$A(s, M_X^2) = A\ln^2(\bar{s}/s_0), \tag{17}$$

$$b(s, M_X^2) = \frac{R_0^2(\bar{s})}{2}, \tag{18}$$

$$\bar{s} = 2(s + M_N^2) - M_X^2. \tag{19}$$

Making the corresponding asymptotic estimates, we can easily obtain the following asymptotic formula for the $p\bar{p}$ single diffraction dissociation cross-sections:

$$\sigma_{SD}^{p\bar{p}}(s) = C\frac{\ln^2(s/s_0)}{c_0 + c_2\ln^2(\sqrt{s}/\sqrt{s_0})}, \tag{20}$$

where

$$c_0 = a_0 - b_0, \quad c_2 = a_2 - b_2, \tag{21}$$

the quantities a_0, b_0, a_2, b_2, $\sqrt{s_0}$ are defined by Eqs.(4,5,6,12,13) and the constant C is undefined. Let us fix the value of C from the measured $\sigma_{SD}^{p\bar{p}} = (7.89 \pm 0.33)\ mb$ at $\sqrt{s} = 546\ GeV$

$$C = (1.72 \pm 0.07)\ mb/GeV^2. \tag{22}$$

Then we come to the asymptotic formula for the $p\bar{p}$ single diffraction dissociation cross-sections with all parameters fixed

$$\sigma_{SD}^{p\bar{p}}(s) = (1.72 \pm 0.07)\frac{4\ln^2(\sqrt{s}/\sqrt{s_0})}{(5.22 \pm 0.21) + (0.41 \pm 0.06)\ln^2(\sqrt{s}/\sqrt{s_0})}\ mb, \tag{23}$$

$$\sqrt{s_0} = (18.99 \pm 1.95)\ GeV.$$

From the formula (23) we obtain the value of $\sigma_{SD}^{p\bar{p}}$ at $\sqrt{s} = 1800\ GeV$

$$\sigma_{SD}^{p\bar{p}} = (10.39 \pm 0.42)\ mb. \tag{24}$$

This value of $\sigma_{SD}^{p\bar{p}}$ is in good agreement with the experimental value $\sigma_{SD}^{p\bar{p}} = (9.46 \pm 0.44)\ mb$ at $\sqrt{s} = 1800\ GeV$ [1].

The extrapolation of formula (23) up to the LHC energies $\sqrt{s} = 16\ TeV$ gives

$$\sigma_{SD}^{p\bar{p}} = (13.10 \pm 0.53)\ mb. \tag{25}$$

It also follows from formula (23) that

$$\lim_{s\to\infty} \sigma_{SD}^{p\bar{p}}(s) = (16.78 \pm 0.68)\ mb. \tag{26}$$

We cannot use equation (23) for the extrapolation down to the lower energies. This formula is an asymptotic one and one needs to account for the preasymptotic terms when, extrapolating to the lower energies. We hope that it will be possible to test the asymptotic formula (23) at higher energies, such as those of the LHC collider.

Acknowledgements

It is our pleasure to thank Professor N.E. Tyurin for the encouraging discussions and Miss Yen Jun Sun for her help in the final preparation of the manuscript.

References

[1] F. Abe et al., (CDF) Phys. Rev. D50 (1994) 5535.

[2] E.S. Martynov, B.V. Struminsky, Proceedings of the XI-th Workshop on "soft" physics HADRONS-95, Novy Svet, Crimea, September 6-11, 1995, eds. G. Bugrij, L. Jenkovsky, E. Martynov, Kiev, 1995, p.53-60.

[3] A.A. Arkhipov. Preprint IHEP 96-66, Protvino 1996. Proceedings of the XII-th Workshop on "soft" physics HADRONS-96, Novy Svet, Crimea, June 9-16, 1996, eds. G. Bugrij, L. Jenkovsky, E. Martynov. Kiev - 1996, p.252-263.

[4] M. Honda et al., Phys. Rev. Lett. 70 (1993) 525.

[5] D. S. Ayers et al., Phys. Rev. D15 (1977) 3105.

[6] D. Favart et al., Phys. Rev. Lett. 47 (1981) 1191.

[7] R. L. Cool et al., Phys. Rev. D24 (1981) 2821.

[8] R. Battiston et al., Phys. Lett. 115B (1982) 333.

[9] N. Amos et al., Phys. Lett. 120B (1983) 460.

[10] G. Arnison et al., Phys. Lett. 128B (1983) 336.

[11] M. Ambrosio et al., Phys. Lett. 115B (1982) 495.

[12] R. Battiston et al., Phys. Lett. 127B (1983) 472.

[13] A. Breakstone et al., CERN-EP-84-105, 1984.

[14] N. Amos et al., Phys. Rev. Lett. 61 (1988) 525.

[15] R. E. Breedon et al., Phys. Lett. 216B (1989) 459.

[16] N. Amos et al., Phys. Lett. 247B (1990) 127.

[17] N. Amos et al., FERMILAB-PUB-91-267, 1991.

[18] N. Amos et al., Nucl. Phys. B262 (1985) 689.

[19] C. Augier et al., Phys. Lett. 316B (1993) 448.

[20] N. Amos et al., Phys. Rev. Lett. 63 (1989) 2784.

[21] F. Abe et al., FERRMILAB-PUB-93-232-E, 1993.

[22] J. Whitmore et al., Phys. Lett. 59B (1975) 299.

Received February 21, 1997

А.А.Архипов, П.М.Надольский
Эффективный радиус трехнуклонных сил и диффракционная диссоциация $\bar{p}p \to \bar{p}X$ при высоких энергиях.

Оригинал-макет подготовлен с помощью системы LaTeX.
Редактор Е.Н.Горина. Технический редактор Н.В.Орлова.

Подписано к печати 27.02.97. Формат $60 \times 84/8$. Офсетная печать.
Печ.л. 1. Уч.-изд.л. 0.76. Тираж 250. Заказ 951. Индекс 3649.
ЛР №020498 06.04.92.

ГНЦ РФ Институт физики высоких энергий
142284, Протвино Московской обл.

Индекс 3649

П Р Е П Р И Н Т 97-6, И Ф В Э, 1997